NASA ESMD

Capstone Design Course

First Annual Space Grant Faculty Senior Design Training

developed by

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and

Director

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Course Scope

Capstone Design based upon a systematic design process

What is Capstone Design?

- How to develop products to exceed customer requirements and expectations
- This is the real thing
- Students synthesize their foundational knowledge and add new skills to deliver

Course Overview

- The Capstone Design course requires that students work in teams on —open-ended” engineering design projects. Students are given the opportunity to realize original and creative solutions to real engineering problems, not merely design changes of scale or duplication of existing systems. Important topics are presented in the lectures, including the design process, design tools, systems engineering, project management, engineering communication, engineering ethics, and intellectual property. Students are encouraged to take on new team roles and to test the limits of their capabilities.

Learning Objectives

- Students will understand the importance of a structured design process
- Students will understand and be able to implement the five phases of a structured systems engineering process
- Students will be able to implement the key tools of a structured design process
- Students will gain practice in working on self-managed teams
- Students will gain confidence in their abilities to deliver an engineering solution from need to parts

ABET Criteria for Engineering Education

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multi-disciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Engineering Design

- … a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints.

  Dym *et al*., —EngineeringDesign Thinking, Teaching, and Learning," *Journal of Engineering Education*, 2005.

- … the process of devising a system, component, or process to meet desired needs. It is a decision- making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.

Criteria for Accrediting Engineering Programs, ABET, 2008.

Engineering Design

- … the communication of a set of rational decisions obtained with creative problem solving for accomplishing certain stated objectives within prescribed constraints. Lumsdaine *et al*., p. 316
- Design establishes and defines solutions and pertinent structures for problems not solved before, or new solutions to problems which have previously been solved in a different way. … The ability to design is both a science and an art. … Good design requires both analysis and synthesis. Dieter, pp.1-3
- Design incorporates creativity, complexity, making choices between many possible solutions, and compromise in balancing many (sometimes conflicting) requirements. Dieter, pp.1-3

What Makes this Course Different?

systems engineering-based, multi-disciplinary design with multi-source projects in a modular implementation

Multi- Multi-

- Multi-disciplinary design
  - One course for all or any majors
  - Can run multi-disciplinary projects with one lecture
  - Design is an application independent science
- Multi-source projects
  - Allow for the speed and risk inherent in industry
  - Allow for the checks and balances inherent in NASA
  - Allow for the systems nature of large competition projects

Design Process Comparison - Stages

NASA	Capstone Design	Lumsdaine
	Pre-Phase A	
Concept Studies	Design Problem Analysis	Design Problem Analysis
	Phase A	
Concept and Technology Development	System Level Conceptual Design	Conceptual (System) Level Design
	Phase B	
Preliminary Design and Technology Completion	Parameter Level Design	Parameter Level Design
	Phase C	
Final Design and Fabrication	Optimized Parameter Design	Optimized Parameter Design
	Phase D	
Assembly, Integration, and Test Launch	Fabrication, Assembly, and Testing	-

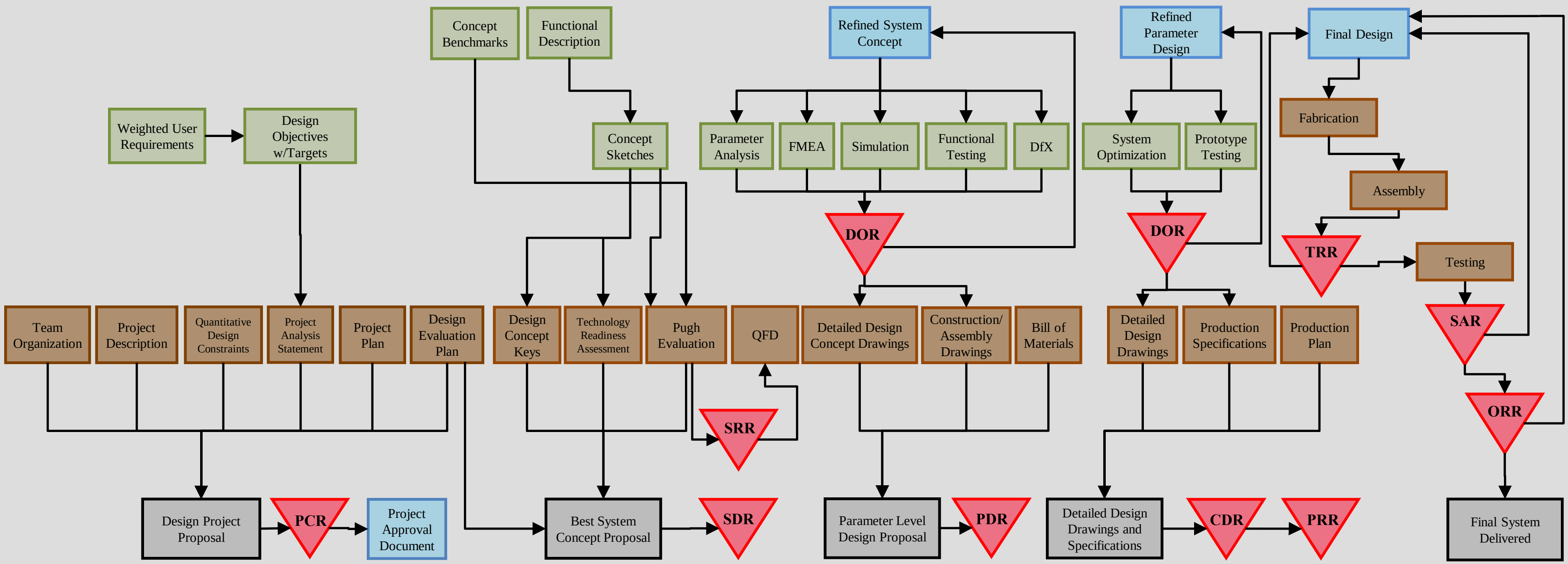
Design Process Comparison – Reviews and *Documents*

NASA	Capstone Design	Lumsdaine
Pre-Phase A		
MCR- Mission Concept Review IPR- Informal Proposal Review *Program/Project Proposals* *Preliminary Mission Concept Report*	PCR- Project Concept Review *Project Approval Document*	Review by Instructor, Advisor, and Sponsor *Design Project Proposal*
Phase A		
SRR- System Requirement Review SDR- System Definition Review	SRR- System Requirement Review SDR- System Design Review	*Design Concept Keys* *Design Decisions*
Phase B		
PDR- Program Definition Review *Preliminary Design Report* *Interface Control Documents*	DOR- Design Objectives Review PDR- Product Design Review *Refined System Concept*	Review by Instructor, Advisor, Team, and Sponsor *Design Project progress Report*
Phase C		
CDR- Critical Design Review PRR- Production Readiness Review *Preliminary Operations Handbook*	DOR- Design Objectives Review CDR- Critical Design Review PRR- Production Readiness Review *Refined Parameter Design*	Design review panel and Instructor – Oral Presentation Review *Final progress Report*
Phase D		
TRR- Test Readiness Review SAR- System Acceptance Review ORR- Operational Readiness Review *Verification and Validation Report* *Operator and Maintenance Manuals*	TRR- Test Readiness Review SAR- System Acceptance Review ORR- Operational Readiness Review *Final Design*	-

Flexible Modules

- One set of modules for many applications
  - Course length
  - Project finish gate
  - Add in major-dependent or project dependent knowledge

Structured Design Process



Pre-Phase A
Design Problem Analysis

Phase A
System Level Conceptual Design

Phase B
Parameter Level Design

Phase C
Optimized Parameter Design

Phase D
Fabrication, Assembly, and Testing

GOALS
STEPS
TOOLS
REVIEW
DOCUMENT

Review Points

PCR- Project Concept Review	**SRR**- System Requirements Review
SDR- System Design Review	**DOR**- Design Objectives Review
PDR - Product Design Review	**CDR** - Critical Design Review
PRR- Production Readiness Review	**TRR**- Test Readiness Review
SAR - System Acceptance Review	**ORR** - Operational Readiness Review

Systems Engineering-based

- Prepare students for the far more common reality of design
  - Each component or sub-assembly must work together within a larger, more complex system
  - That may be a system of components, assemblies, or even products
- Systems integration and systems engineering should be a focus of capstone projects and syllabi
  - Student competition projects
    - Challenge X, Formula Car, Human Powered Vehicle, *etc*.
  - Opportunities within NASA and DoD
- Difficult to drop such projects into most STEM capstone design curricula
  - Due to the complexity and multi-disciplinary nature of such projects
  - Often done outside the bounds of the typical program path.

Systems Engineering Process

objectives, key functions

Systems Engineering

- Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system
- A —system” is a construct or collection of different elements that together produce results not obtainable by the elements alone

Objective

- "The objective of systems engineering is to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule and risk."
  – NASA Systems Engineering Handbook SP-6105

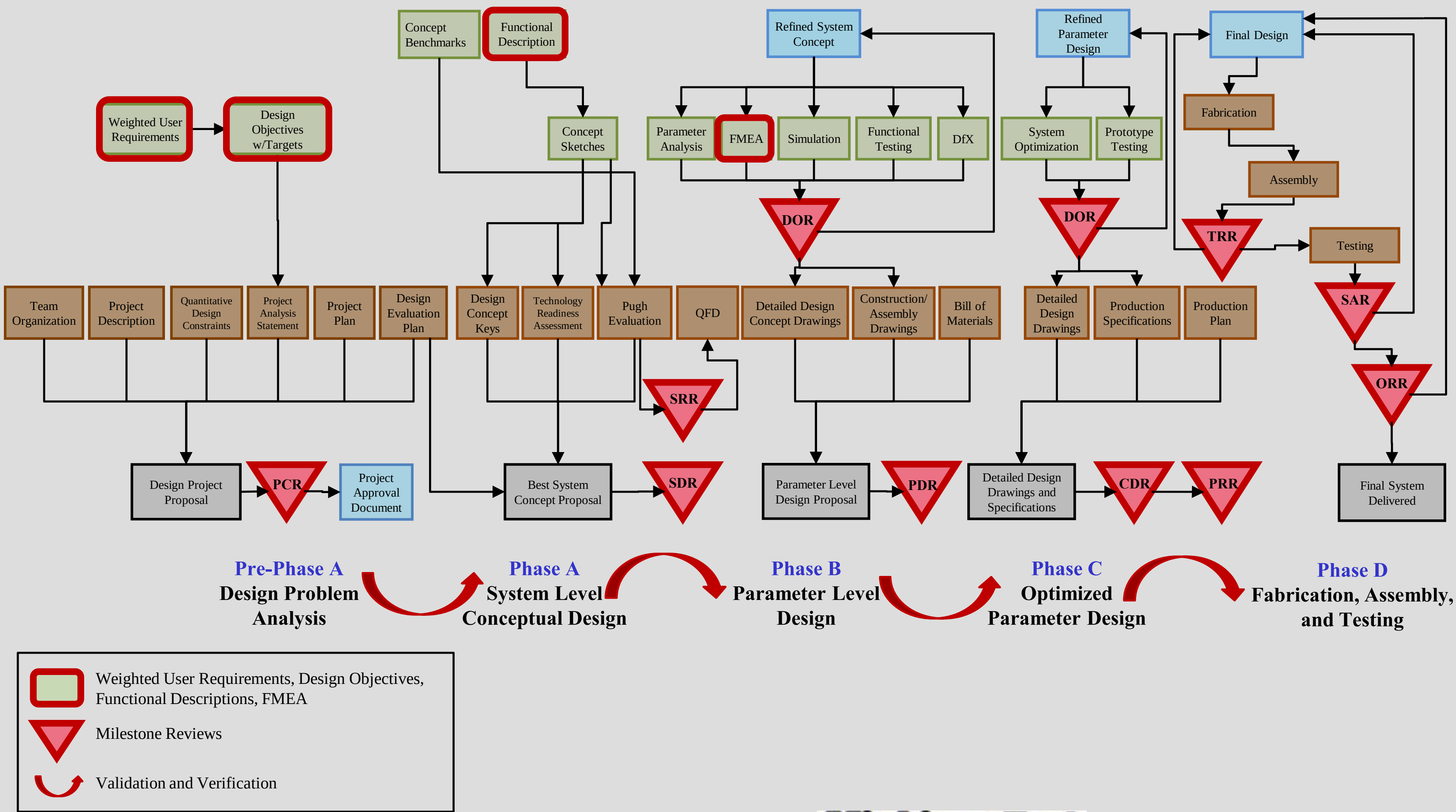
System Engineering Functions

- Major functions that lay the ground work for a robust approach to the design, creation, and operation of system

Key SE Functions

- Design objectives and constraints
- Weighted user requirements
- Functional descriptions
- Validation and verification
- Interfaces and ICDs
- Milestone reviews
- Risk management

Key SE Functions in the Design Process



Design Objectives and Constraints

- *When?*
  - Pre-Phase A: Design Problem Analysis
- *What?*
  - Clearly define and document the design goals to make sure that the team is working towards a common goal
  - Capture quantitative constraints which can be used to validate product design

Weighted User Requirements

- *When?*
  - Pre-Phase A: Design Problem Analysis
- *What?*
  - Establish the various requirements
    - functional, performance, interface, environmental, *etc*.
  - Formally document requirements
  - Refine requirements by conducting trade studies

Functional Descriptions

- *When?*
  - Phase A: System Level Conceptual Design
- *What?*
  - Goal is to develop an architecture and design that meets requirements
  - Block diagrams are key mechanism for documenting and communicating the functional analysis and architecture to the team

Validation and Verification

- *When?*
  - Takes place over the systems engineering lifecycle to show that systems of interest meets the objective

Validation

- Assure design meets the *objectives*
  - For example, validate the ICDs to weighted user requirements and functional descriptions and architecture

Verification

- Verify the design against the *requirements*
  - Use as an important risk reduction measure
  - Carry out functional tests and simulations as in Phase B
  - Using a Critical Design Review (CDR) in Phase C, assign the requirements a verification method
  - Verify the requirements in Phase C and D using the Production Readiness Review (PRR) and Operational Readiness Review (ORR) respectively
  - Review of the verification results is particularly effective in identifying and correcting problems

Interfaces and ICDs

- *When?*
  - Before Phase C
  - Establish before Product Design Review (PDR) to allow detailed design to proceed with minimal risk of changes
- *What?*
  - Describe and document where and how various system elements need to connect or communicate with each other

Milestone Reviews

- *When?*
  - Between and during all phases
- *What?*
  - Validate the quality and completeness of a system engineering phase or portion thereof
  - Facilitate knowledge sharing and identification and resolution of challenges and issues

Risk Management

- When?
  - Apply various tools at appropriate phases
- What?
  - Perform FMEA at Parameter level design during Phase B
  - Report results of FMEA at critical milestone reviews
  - Use other tools like FTA, reliability analyses, *etc*.

Course Structure

audience, syllabus, projects, process, modules, lectures, texts, facilities, grading

Student Audience

- Capstone Design is intended for engineering students that have completed all of the core requirements of their education
- The purpose of the course is to teach students how to implement a structured design process on a real project in a team (perhaps multi-functional) environment
- Teams can contain a mix of students in various years as long as they are all exposed to the design process material

Faculty Audience

- The lecturer for this course may be different from the advisor(s)
- The lecturer should have familiarity and experience with structured design
- Faculty should use these modules as a text from which they will design their own course, possibly adding material

Syllabus

- A sample syllabus follows

MEEM XXXX – Senior Design

TR 12:05-1:25 in DOW 641, Fall 2XXX / Spring 2XXX

Instructor:	Dr. John Gershenson Office: XXXX Phone: XXXX E-mail: XXXX	**Administrative Asst:**	XXXX Office: XXXX Phone: XXXX E-mail: XXXX
Project Dir:	XXXX Office: XXXX Phone: XXXX E-mail: XXXX	**Fabrication Asst:**	XXXX Office: XXXX Phone: XXXX E-mail: XXXX

Pre-requisite: MEEM XXXX or pre-requisites for senior design in your major.

Objective: The Senior Design course requires that students work in teams on "open-ended" engineering design projects. Students are given the opportunity to realize original and creative solutions to real engineering problems, not merely design changes of scale or duplication of existing systems. Important topics are presented in the lectures including the design process, design tools, project management, engineering communication, engineering ethics, and intellectual property. Students are encouraged to take on new team roles and to test the limits of their capabilities.

Design Project: Each student will participate in a team project. This is the most important element of the class. The project is designed to be your first project outside of school and should be treated as a job. The goal is to give you that experience with fewer ramifications for project failure. Each person will be expected to participate in the team and work on the project professionally. On each of the projects, there are individuals and companies making a significant investment in your success. If you are in this class, it means we believe you are capable in giving these individuals a more than satisfactory return on that investment. Each sponsor and advisor will expect a finished, documented project completed to his or her expectations. You will be graded against those expectations. The advisor and sponsor will also be responsible for your success. The role of your advisor is to help guide you through the design process, offer advice when appropriate, steer you when necessary, and help you find information when necessary. This is accomplished through at least one weekly, hour-long meeting. The advisors are neither your sole source for technical information nor perhaps your primary source. The sponsors represent their own interests. We are expected to serve those interests within the guidelines set by the advisor. Groups should meet frequently with their sponsors – in person and by teleconferencing or videoconferencing. Administrative Asst is responsible for all financial issues with the projects. Either Project Dir or Dr. Gershenson is responsible for all sponsor issues.

Class Preparation: Students will be expected to prepare all reading and written assignments *before* class. Class notes will be available electronically by 9AM class day. Individual attendance and participation in class is necessary. Lectures are geared towards the success of your projects. Speakers will be brought in for your information; they should not meet a half empty class. This is part of the professionalism expected at your level. If attendance suffers, a stricter policy will be adopted. In the fall, we will meet twice a week for lectures. In the spring, class will meet only once per week with very few lectures.

Text: Main text: *Creative Problem Solving and Engineering Design,* Edward Lumsdaine, Monika Lumsdaine, and J. William, Shelnutt, McGraw-Hill College Custom Series, New York, 1999. Additional suggested texts: *Engineering Design,* 3rd edition, George E. Dieter, McGraw-Hill, Boston, 2000 suggested, one copy per team minimum. Other texts include: *A Guide to Writing as an Engineer,* David Beer and David McMurrey, John Wiley & Sons Inc., New York, 1997 (Ref. 1 in the reading list) and *Patent Fundamentals for Scientists and Engineers,* 2nd Edition, Thomas T, Gordon and Arthur S. Cookfair, Lewis Publishers, CRC Press LLC, Boca Raton, 2000 (Ref. 2 in the reading list). All students planning to be design engineers should own a design text.

Course and Project Web page: This course has a web page that contains all of the pertinent course materials, grading forms, notes, and tools – www.XXXX.

Grading: The goal of the course is to learn how a successful project is run and to deliver on a real project. The grading scheme for the class is fairly complex due to the team structure, the nature of the advisors and sponsors, and the difficulty in assessing some elements of your work. This year, we will again use a somewhat novel, paper intensive scheme designed to better inform students and advisors of how individuals are performing and take away the awkwardness of pre-planned assignments. Each group will receive a grade each semester. **The individuals in the group will receive grades that average out to that group grade.** YOU MUST RECEIVE AN INDIVIDUAL GRADE OF C/D OR BETTER IN 4900 TO CONTINUE IN 4910 (THERE WILL BE NO Ds GIVEN AND NO INCOMPLETES)!!!! My grading scale is as follows: A (92.5+), A/B (87.5-92.5), B (82.5-87.5), B/C (77.5-82.5), C (72.5-77.5), C/D (67.5-72.5).

Group Work: (62.5%) Twice per semester your advisor and your sponsor will be given a form to grade your groups performance. The graded elements on both forms are quality of work (100pts), quantity of work (100pts), professionalism (50pts), and communication (50pts). In addition, the sponsor will grade whether you are making good progress (50pts). All grades are relative to the advisors' and sponsors' expectations. An average senior design project should receive about 85% of the points. There will be no curving of grades.

Report: (25%) Each group will complete one report at the end of each semester to be graded equally by the advisor and myself. The structure of the class and required work should lead to a minimum of time spent writing the reports at the end of the semester. If you find the reports time consuming, there was a missed opportunity to complete sections earlier in the semester. The report will be graded by the advisor for communication quality (30pts) and use of each of the class tools (points depend upon tool), and by myself for communication quality (30pts), completeness of work (30pts), use of class tools (points depend upon tool), holding to the format (10pts), and one or two other issues.

Presentation: (12.5%) There will be only one presentation per semester in approximately the 14^{th} week. The group must schedule a room and time with the TA in charge. The presentation must be attended (or viewed) by your advisor, YOUR SPONSOR, and one other 4900 advisor. Each student must also attend at least three other presentations. One TA or instructor will attend. Your presentation grade will be an average of the evaluations of all those attending. Your poster will be judged at this time too and incorporated in the presentation grade.

Individual Grade: (averaged around the group grade) Your advisor will grade each student twice per semester based on quality of work (100pts), quantity of work (100pts), and professionalism (50pts). Your advisor may choose to ask each student to fill out self-evaluations or teammate evaluations during the semester. YOUR DESIGN JOURNAL/PORTFOLIO WILL BE A MAJOR SOURCE OF INFORMATION FOR YOUR INDIVIDUAL GRADE.

Advisor Feedback: Twice each semester students and sponsors will be able to give feedback to the advisors in the form of a short evaluation on availability, interest, communication, and other issues. Your feedback will be anonymous.

Facilities: It is possible to complete your project (and product) within the university, but it is not required. Depending upon the project's budget, work can be done "out of house." Each team will have a design studio assigned to them, which should suffice all team meeting and Sun computing needs. PC needs can be met on the first floor. Teleconferencing and videoconferencing is possible through arrangement with Administrative Asst. Prototyping capabilities are available on the first floor through Fabrication Asst. Poster printing is available through WE Support. Testing needs can be met by contacting XXXX in the basement. Fabrication facilities are available XXXX under the direction of Fabrication Asst. Each student must be approved for the machines in the shop, please take care of that approval early in the first semester when Mr. Rowe is more available. Anyone can be approved; Fabrication Asst is

MEEM XXXX – Senior Design

Dr. John Gershenson

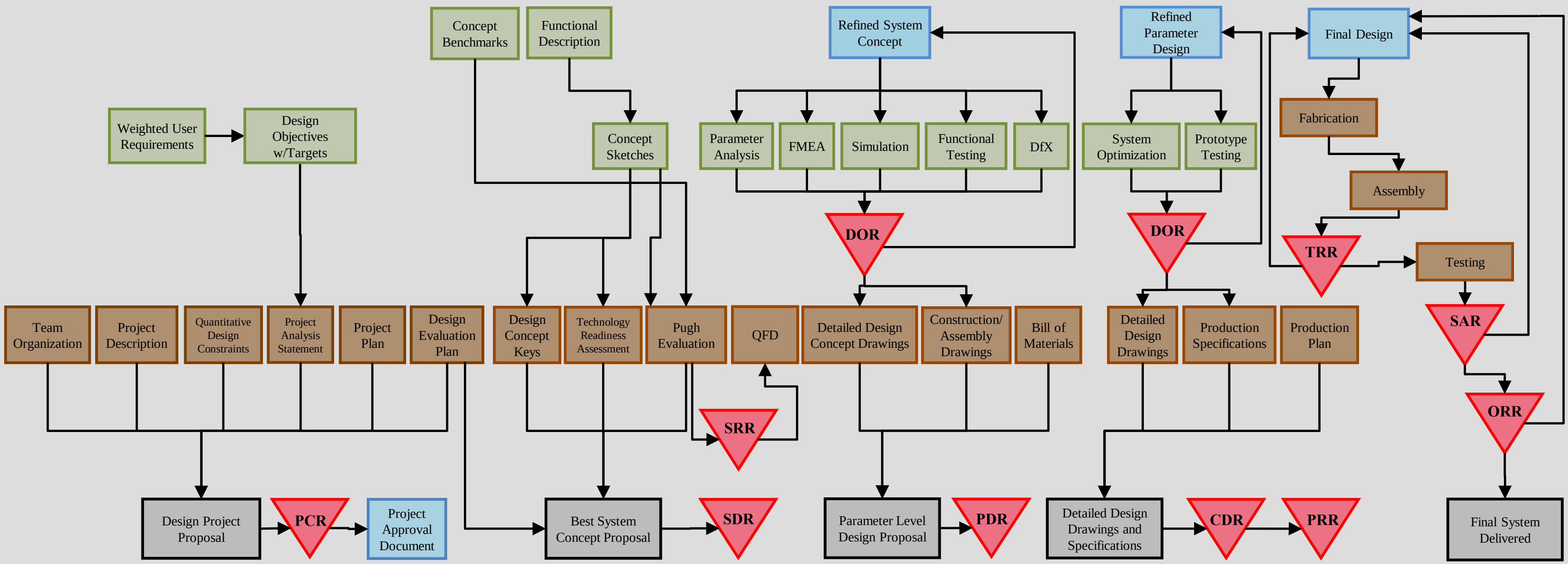
Module	Description	Readings*	Deliverables	Reviews
00	Course Introduction	Syllabus, Ch. 1		
01	The Design Process	Ch. 13, 14	Project Assignment Sheet	
02	Team Organization	Ch. 3, 4, 5	Team Ground Rules, HBDI Analysis	
03	Project Description	Ch. 7	Project Description	
04	Project Requirements	App B, Handout	Quantitative Design Constraints, Project Analysis Statement	
05	Project Planning	Ch. 15	Project Plan, Design Evaluation Plan, *Design Project Proposal*	**PCR**
06	Conceptual Design	Ch. 8, 6, 9	Design Concept Keys, Technology Readiness Assessment	
07	Pugh Evaluation	Ch. 10, 11	Pugh Evaluation	SRR
08	Quality Function Deployment	App A, Handout	Quality Function Deployment	
09	System Design Review	Handout	*Best System Concept Proposal*	**SDR**
10	Failure Modes and Effects Analysis	App D, Handout	Failure Modes and Effects Analysis	
11	Design-for-X	Handout	Design-for-X	
12	Parameter Analysis	Handout	Parameter Analysis, Functional Testing, Simulation	DOR
13	Parameter Level Design Proposal	Handout	Detailed Design Concept Drawings, Construction/Assembly Drawings, Bill of Materials, *Parameter Level Design Proposal*	**PDR**
14	System Optimization	Handout	System Optimization	
15	Prototyping and Testing	Handout	Tested Prototype	DOR
16	Detailed Design Drawings	Handout	Detailed Design Drawings, Production Specifications?, Production Plan?, *Detailed Design Drawings and Specifications*	**CDR/PRR**
17	Fabrication, Assembly, and Testing		**Final System**	TRR/SAR/ORR?

Note: Course material is subject to change.
*from the combined text *Creative Problem Solving* (Lumsdaine *et al.*) and *Engineering Design 2* (Dieter)

Projects

- Teams of four or more students work on one sponsored project lasting two semesters
- Projects encompass the entire design process — ideation through functional prototype build and evaluation
- First semester ends with a formal project review, reflective of a typical stage-gate process, in which each team demonstrates their design progress to date and gain approval for their plan to complete the project during the second semester
- Second semester concludes with a project-ending presentation before industry representatives, faculty members, and peers
- Typical projects are design-intensive, where the team may be asked to develop a new product, design and build a portion of a new manufacturing process cell, or fabricate a special machine designed for a specific task

Capstone Design Process



Pre-Phase A
Design Problem Analysis

Phase A
System Level Conceptual Design

Phase B
Parameter Level Design

Phase C
Optimized Parameter Design

Phase D
Fabrication, Assembly, and Testing

GOALS
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Review Points

PCR- Project Concept Review
SDR- System Design Review
PDR - Product Design Review
PRR- Production Readiness Review
SAR - System Acceptance Review
SRR- System Requirements Review
DOR- Design Objectives Review
CDR - Critical Design Review
TRR- Test Readiness Review
ORR - Operational Readiness Review

Abbreviations and Acronyms

CDR	Critical Design Review
DfX	Design-for-X
DOR	Design Objectives Review
FMEA	Failure Modes and Effects Analysis
ORR	Operational Readiness Review
PCR	Project Concept Review
PDR	Product Design Review
PRR	Production Readiness Review
QFD	Quality Function Deployment
SAR	System Acceptance Review
SDR	System Design Review
SRR	System Requirements Review
TRR	Test Readiness Review

Learning Modules

Module	Description
00	Course Introduction
01	The Design Process
02	Team Organization
03	Project Description
04	Project Requirements
05	Project Planning
06	Conceptual Design
07	Pugh Evaluation
08	Quality Function Deployment
09	System Design Review
10	Failure Modes and Effects Analysis
11	Design-for-X
12	Parameter Analysis
13	Parameter Level Design Proposal
14	System Optimization
15	Prototyping and Testing
16	Detailed Design Drawings
17	Fabrication, Assembly, and Testing

Module Structure

- Designed as training modules
  - Not necessarily one day
  - Not necessarily in a traditional class setting
  - Treat them as engineers, not students
- Module structures are parallel
  - Teach structured design tools with “traditional” and —space” examples
  - Relate it to the overall process and project deliverables
    - Integrate reviews and reports
  - Offer additional examples that relates to their projects and motivate the importance of systematic design
  - Offer additional readings

Lecture/Project Integration

- It is important to keep the project as the topic of the lecture
- All lecture topics should be framed in terms of what students need to do on their projects
- Students MUST use a structured design process, even when less formal procedures would suffice
- It is my feeling that additional, non-project assignments and exams do not add to the quality of the learning and can cause –mutinies"

Assignments

- If it is necessary for the course (as opposed to the advisor and the project) to dictate assignments, make sure that the assignments are part of the critical path of ALL projects
- One significant issue with sponsored projects (or even different projects) is that they will have differing milestone timelines and make blanket due dates impractical

Notes

- The notes in this course are designed for you to give to your students BEFORE the lecture
- You can then use your knowledge of the design process and your design experiences to help them —"fill in the gaps" during lectures

Texts

- Main text
  - *Creative Problem Solving,* Edward Lumsdaine, Monika Lumsdaine, and J. William, Shelnutt, McGraw-Hill, New York, 1995
  - *Engineering Design 2*, George E. Dieter, McGraw-Hill, New York, 2000
- Additional suggested texts
  - *Engineering Design,* 3rd Edition, George E. Dieter, McGraw-Hill, Boston, MA, 2000
  - *A Guide to Writing as an Engineer,* David Beer and David McMurrey, John Wiley & Sons Inc., New York, 1997
  - *Patent Fundamentals for Scientists and Engineers,* 2nd Edition, Thomas T. Gordon, and Arthur S. Cookfair, Lewis Publishers, CRC Press LLC, Boca Raton, FL, 2000

Additional References

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  - Bahill, T.A. and Gissing, B., Re-evaluating System Engineering Concepts Using Systems Thinking, IEEE Trans. on Systems, Man and Cybernetics, v.28(4), p.516-527, 1998.
  - System Engineering Paper Submission Template, http://education.ksc.nasa.gov/ESMDspacegrant/SE_Paper_Submission_Template.doc
  - Blanchard, B.S. and Fabrycky,W.J., System Engineering and Analysis, 2nd edition, Prentice Hall, 1990.
  - ANSI/EIA 632-1998, Processes for Engineering a System, Electronic Industries Alliance, 1999.
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  - Raju, P.K. and Sankar, C.S. Introduction to Engineering with the Use of Case Studies, Institute for STEM Education and Research, 2007.
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  - Larson, W.J. (Editor) and Wertz, J.R. (Editor), Space Mission Analysis and Design, 3rd edition, Space Technology Library.
  - Fortescue, P. (Editor), Stark, J. (Editor), and Swinerd, G. (Editor), Spacecraft Systems Engineering, 3rd edition, Space Technology Library.
  - Sarafin, T.P. and Larson, W.J. (Editor), Spacecraft Structures and Mechanisms from Concept to Launch, The Space Technology Library
  - Space Vehicle Mechanisms: Elements of Successful Design (Hardcover) by Peter L. Conley
  - The Space Environment: Implications for Spacecraft Design (Paperback) by Alan C. Tribble (Author)
  - Space Vehicle Design (Aiaa Education Series) (Hardcover) by Michael D. Griffin (Author), James R. French
  - Fundamentals of Space Systems (The Johns Hopkins University/Applied Physics Laboratory Series in Science and Engineering) (Hardcover) by Vincent L. Pisacane
  - Principles of Space Instrument Design (Cambridge Aerospace Series) (Paperback) by A.M. Cruise (Author), J.A. Bowles (Author), T.J. Patrick (Author)
  - Elements of Spacecraft Design (Aiaa Education Series) (Hardcover) by Charles D. Brown
  - Spacecraft Power Systems (Hardcover) by Mukund R. Patel (Author)
  - Spacecraft Thermal Control Handbook: Fundamental Technologies (Hardcover) by David G. Gilmore
  - Spacecraft Power Technologies (Space Technology) (Hardcover) by Anthony K. Hyder (Author), Ronald L. Wiley (Author), G. Halpert (Author), Donna Jones Flood (Author), S. Sabripour

Additional References

- Space Systems
  - Aircraft Structures for Engineering Students, Fourth Edition (Elsevier Aerospace Engineering) (Paperback) by T.H.G. Megson (Author)
  - Printed circuits in space technology: Design and application (Prentice-Hall space technology series) by Albert E Linden
  - Human Spaceflight: Mission Analysis and Design (Space Technology Series) (Space Technology Series) by Wiley J. Larson and Linda K. Pranke
  - Solar Power Satellites: The Emerging Energy Option (Ellis Horwood Library of Space Science and Space Technology. Series in Space Technology) by Peter E. Glaser, Frank Paul Davidson, and Katlinka I. Csigi
  - Spacecraft structures (Prentice-Hall international series in space technology) by Carl C Osgood (Unknown Binding - 1966)
  - Cryogenic engineering (Prentice-Hall international series in space technology) by Joseph H Bell (Unknown Binding - 1963)
  - Space mechanics (Prentice-Hall international series in space technology) by Walter C Nelson (Unknown Binding - 1962)
  - Navigation and guidance in space (Prentice-Hall international series in space technology) by Edward V. B Stearns
  - THE SECOND FIFTEEN YEARS IN SPACE: SCIENCE AND TECHNOLOGY SERIES: VOLUME 31: by Saul Ferdman (Editor)
  - The Lunar Base Handbook (Space Technology Series) by Peter Eckart (Paperback - Dec 1, 1999)
  - Technologies of manned space systems (Space flight technology series) by Aleck C Bond (Unknown Binding - 1966)
  - Metallurgical Assessment of Spacecraft Parts, Materials and Processes (Wiley-Praxis Series in Space Science and Technology) by Barrie D. Dunn and M. Phil (Paperback - Jun 1997)
  - Satellite Control: A Comprehensive Approach (Wiley-Praxis Series in Space Science and Technology) by John T. Garner Introduction to space communication systems (McGraw-Hill series in missile and space technology) by George N. assner
  - Robots in Space: Technology, Evolution, and Interplanetary Travel (New Series in NASA History) by Roger D. Launius and Howard E. McCurdy (Hardcover - Jan 7, 2008)
  - Recent Developments in Space Flight Mechanics (Science and Technology Series Volume 9) by Paul B. (editor) Richards (Hardcover - 1966)
  - The Lunar Sourcebook (Heiken *et al.*) is a good reference. Chapter 3 covers the lunar environment.
  - http://insa.netquire.com/docs/Lessons_Learned_Fina.pdf

Facilities

- Students need facilities to conduct team meetings without being interrupted, to conduct phone/video conferences with sponsors, to fabricate their prototypes/deliverables, and to do assembly and testing
- Do not underestimate the resources for this
  - Space for projects
  - Personnel for a safe fabrication

Fabrication

- This course is not a course in how to use a fabrication shop
  - That is an important class for engineers, but it is expected that students have completed such a course beforehand
- It should be possible for them to complete their project (and product) within the university, but it is not required
- Depending upon the project's budget, work can be done "out of house"
- Working with contract fabrication allows students to learn much more about engineering communication

Grading

- Each sponsor and advisor will expect a finished, documented project completed to his or her expectations
- It is important to grade against those expectations as well as the students' use of a structured design process and the tools therein

Roles

students, advisors, sponsors

Student Role in Projects

- Each student will participate in a team project
- This is the most important element of the class
- The project is designed to be their first project outside of school and should be treated as a job
- The goal is to give them that experience with fewer ramifications for project failure
- Each person will be expected to participate in the team and work on the project professionally
- Each sponsor and advisor will expect a finished, documented project completed to their expectations

Advisor

- The advisor and sponsor are also responsible for project success
- The role of the advisor is to help guide the team through the design process, offer advice when appropriate, steer when necessary, and help find information when necessary
- This is accomplished through at least one weekly, hour-long meeting
- The advisors should not be expected to be the sole source for technical information nor necessarily the primary source

Sponsor

- The advisor and sponsor are also responsible for project success
- The sponsors represent their own interests
- The team is expected to serve those interests within the guidelines set by the advisor
- Groups should meet frequently with their sponsors – in person and by teleconferencing or videoconferencing

Projects

why and what

Why a Sponsored Project?

- This course is developed around having sponsored projects
- Ideally the projects are paid for by an outside group that is truly committed to the project
- This commitment gives the project financial resources as well as a —customer”
- Even if there is no financial commitment, each project should have a customer that is external to the class that —needs” the final product
- It is important to remind sponsors that not all student projects are successful

Project Description

Project Concept Statement

Design of a Lunar Penetrator to collect one meter of regolith sample

Surface penetrators have been launched in the past by NASA space missions to Mars, which have failed to provide the intended outcome. According to the investigation results from the Mars mission, the failure is attributed to the inability of the communication system to transmit mission data to earth stations via the orbiting satellite. This may be due to the failure of the penetrator and communication hardware to survive impact.

The internal structure of the moon is still not well understood. Acquisition of further knowledge about the lunar core can help us to understand the moon's early history. The regolith sample can provide us with information on the presence of water and other organic volatiles which is relevant to assess lunar evolution and the possibility of future lunar resources. This information reflects the core interests of NASA's lunar missions, making them the main sponsor for this project to coordinate the primary design requirements and specifications.

Our main objective is to design and possibly test a sub-scale prototype of a lunar penetrator that demonstrates key attributes including survival of great impact forces, compliance with weight and dimensional constraints, and the ability to interface with various scientific instruments. The objective will be achieved by following a structured design methodology, progressing from the design problem analysis stage through the optimized parametric design stage. During this entire design process, various design tools will be used to achieve the desired objectives and minimize the risk of failure. Detailed design drawings and specifications will be delivered by February 2009, possibly followed by the fabrication of a sub-scale prototype.

Issues

instructors, material, workload, examples

Instructor Background

- Instructors (lecturers) MUST have a solid background in the fundamentals of the structured design process as well as design experience
  – This is often a shortcoming of some faculty that are asked to teach capstone design

Instructor "Credit"

- Young faculty tend to drown and tend to get put here
- Faculty need to learn to teach before they can advise
- Advising four projects over a year = one semester long course

Student Capability

- There seems to be significant concern with the level of the material and students' capabilities
  - We have taught most of this material to senior undergraduates in the past (even juniors)
  - This is material that many will need to become design engineers
  - Faculty can choose to omit topics if their students are having difficulty

Amount of Material

- There was considerable concern that there is more material than can be taught in a course
  - I agree, use this as a text and pick and choose which topics you feel are necessary
  - Modules 11, 15, 16, and 17 are included as ‘B’ topics
- Course is designed as three hours of class (lecture) time per week for two semesters

Project/Meeting Hours

- There was some concern about whether the capstone projects can be completed in a year and the number of meeting hours required
  - From our experience projects can go from needs definition to finished quality hardware in 25-28 class weeks
  - Student groups should be self-managed to some degree and meet with their advisor for roughly one hour a week
  - Groups should also meet with their sponsor for roughly one hour per week, ideally with their advisor present
  - Sponsor and advisor involvement are key to project success

Project Examples

- Lunar penetrator is followed as a consistent example throughout the entire course
- Supplemented with pieces from text and other examples
- Appended to this presentation

NASA ESMD

Capstone Design Course

First Annual Space Grant Faculty Senior Design Training

developed by

John K. Gershenson, Ph.D.

Professor of Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

and

Director

thebenshimagroup

thebenshimagroup

Design of a Lunar Penetrator

NASA ESMD Capstone Design

Project Description

Project Concept Statement

Design of a Lunar Penetrator to collect one meter of regolith sample

Surface penetrators have been launched in the past by NASA space missions to Mars, which have failed to provide the intended outcome. According to the investigation results from the Mars mission, the failure is attributed to the inability of the communication system to transmit mission data to earth stations via the orbiting satellite. This may be due to the failure of the penetrator and communication hardware to survive impact.

The internal structure of the moon is still not well understood. Acquisition of further knowledge about the lunar core can help us to understand the moon's early history. The regolith sample can provide us with information on the presence of water and other organic volatiles which is relevant to assess lunar evolution and the possibility of future lunar resources. This information reflects the core interests of NASA's lunar missions, making them the main sponsor for this project to coordinate the primary design requirements and specifications.

Our main objective is to design and possibly test a sub-scale prototype of a lunar penetrator that demonstrates key attributes including survival of great impact forces, compliance with weight and dimensional constraints, and the ability to interface with various scientific instruments. The objective will be achieved by following a structured design methodology, progressing from the design problem analysis stage through the optimized parametric design stage. During this entire design process, various design tools will be used to achieve the desired objectives and minimize the risk of failure. Detailed design drawings and specifications will be delivered by February 2009, possibly followed by the fabrication of a sub-scale prototype.

Design Project Proposal

Design Problem Statement

Design Problem Statement

It is desirable to gain knowledge about the lunar core. This knowledge can help us with useful information on the presence of water and other organic volatiles that can help to assess lunar evolution and possibility of future lunar resources.

No successful surface probes have been launched until now to the lunar surface. A Mars surface probe has been launched in the past but failed to send data back to the earth stations. The possible causes of failure were:

- Inability of the radio equipment to survive impact
- The probe hitting rocky surface
- Malfunction with the battery

We aim to design the lunar penetrator keeping all these factors in mind. The penetrator including the radio must be robust enough to survive all impact. The battery must be operational after impact for a period of one day and must power all the radio and scientific equipment. Our concept will be a missile shaped penetrator which will demonstrate all of these attributes analytically. A subscale prototype will be built and tested on surface resembling the lunar surface to evaluate the predicted performance. The penetrator shell will be designed to protect all equipment that is housed within by selecting appropriate materials and design parameters. All possible failure modes will be identified and risk of failure will be eliminated.

3

Design Constraints

Design Constraints for the Lunar Penetrator

Constraints	Method of Measurement	Target	Acceptable Limits
Impact angle	Angle [in degrees]	90°	60°-90°
Length of soil sample	Length of penetration [m]	1 m	1.20 m
Location of impact	Particle size [µm]	50 µm	30- 100 µm
Mass of Penetrator	Mass [kg]	<35 kg	<40 kg
Length of penetrator	Length from tip to end of antenna [m]	< 2 m	< 2.5 m
Survive impact shock load	Impact force [G]	8000 G	>8000 G
Thermal constraints	Lowest endurable temperature	-55° C	-55° C
Data transmission	Date transfer rate [bits/sec]	9600 bits/sec	9,000 bits/sec - 10,000 bits/sec
Battery power	Capacity [Ah] needed to ensure functionality for specified lifetime	375 Ah	350 – 450 Ah
Cost	Cost of prototyping/ testing [$]	$3500	< $4000
Lifetime	Operational time	Regolith analysis: 1 transmission Other instruments: 1 year	Regolith analysis: >1 transmission Other instruments: >1 year
Accommodation of scientific payload	Capability of standard interfacing with scientific payload	Single interface	2-3 interfaces

Design Objectives with Targets

Updated Design Objectives w/ targets for Lunar Penetrator

Design Objective	Weight	Design Estimation	Target
Low weight	10	Estimate the weight by volume of material in each part plus the weight of the payload	<35[kgs]
Low cost	10	Estimated total cost for prototyping and testing	<$4200
High strength and non corrosive material	20	Strength index	High impact strength
Space for accommodation of instruments *etc.*	10	Have at least A compartments of Φ50mm×50mm in height	A=3
Eliminate the risk of failure on impact due to movement of parts	20	N number of movable parts	N=0
To build an outer shell to protect payload from extreme temperature variations	10	Thermal resistance R	High thermal resistance
Adequate power supply by batteries	25	Capacity C	C = 300Ah
Lifetime of shell	5	Operating time t	t= 1 year

Design Evaluation

Design Evaluation

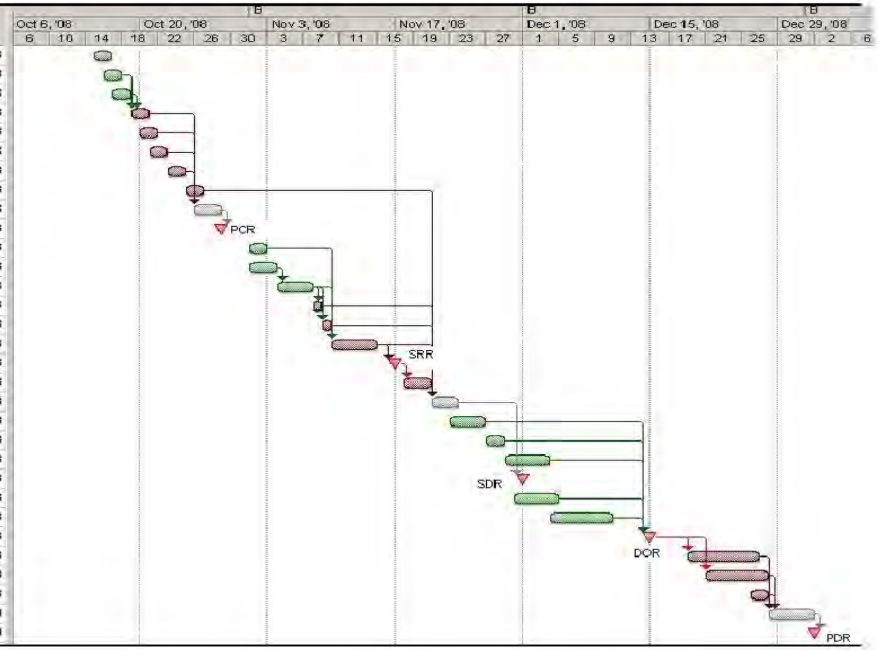
- After the completion of the detailed design of the Lunar Penetrator, a subscale prototype will be fabricated. This prototype will be tested subject to successful completion of the Test Readiness Review by impacting it on surfaces that resemble the lunar surface and soil characteristics.
- The Lunar Penetrator design will be analytically evaluated using computer simulation methods like Finite Element Analysis during the Parameter Level Design Stage. This will be done to evaluate the survivability of the penetrator (consisting of the nose, body and the telemetry system) in conditions of high impact forces. This is vital to ensure the protection and function of the scientific and communication equipment.
- The design will be evaluated by external consultants.

6

Project Plan

Project Plan

	Task Name	Duration	Start	Finish
1	Identify User Requirements	2 days?	Wed 10/15/08	Thu 10/16/08
2	Set Design Objectives and Targets	2 days?	Thu 10/16/08	Fri 10/17/08
3	Conduct Trade-Off Analysis	2 days?	Fri 10/17/08	Sat 10/18/08
4	Write Project Analysis Statement	2 days?	Sun 10/19/08	Mon 10/20/08
5	Write Project Description	2 days?	Mon 10/20/08	Tue 10/21/08
6	Define Quantitative Design constraints	2 days?	Tue 10/21/08	Wed 10/22/08
7	Write Project Plan	2 days?	Thu 10/23/08	Fri 10/24/08
8	Write Design Evaluation Plan	2 days?	Sat 10/25/08	Sun 10/26/08
9	Develop Design Project Proposal	3 days?	Sun 10/26/08	Tue 10/28/08
10	Prepare Project Concept Review	1 day	Wed 10/29/08	Wed 10/29/08
11	Define Concept Benchmarks	2 days	Sat 11/1/08	Sun 11/2/08
12	Write Functional Descriptions	3 days	Sat 11/1/08	Mon 11/3/08
13	Create Concept Sketches	4 days	Tue 11/4/08	Fri 11/7/08
14	Write Design Concept Keys	1 day	Sat 11/8/08	Sat 11/8/08
15	Write Technology Readyness Assesment	1 day?	Sun 11/9/08	Sun 11/9/08
16	Prepare Pugh Evaluation	5 days	Mon 11/10/08	Fri 11/14/08
17	Prepare System Requirements Review	1 day?	Mon 11/17/08	Mon 11/17/08
18	Apply QFD	3 days	Tue 11/18/08	Thu 11/20/08
19	Write Best System Concept Proposal	3 days	Fri 11/21/08	Sun 11/23/08
20	Prepare Parameter Analysis	4 days	Sun 11/23/08	Wed 11/26/08
21	Prepare FMEA	2 days	Thu 11/27/08	Fri 11/28/08
22	Prepare Simulation	5 days	Sat 11/29/08	Wed 12/3/08
23	Write System Design Review	1 day?	Mon 12/1/08	Mon 12/1/08
24	Functional Testing	5 days?	Sun 11/30/08	Thu 12/4/08
25	Prepare DfX- Analysis	7 days?	Thu 12/4/08	Wed 12/10/08
26	Prepare Design Objectives Review	1 day?	Mon 12/15/08	Mon 12/15/08
27	Prepare Detailed Design Concept Drawings	8 days?	Fri 12/19/08	Fri 12/26/08
28	Prepare Construction/Assembly Drawings	7 days?	Sun 12/21/08	Sat 12/27/08
29	Write Bill of Materials	2 days	Fri 12/26/08	Sat 12/27/08
30	Write Parameter Level Design Proposal	5 days	Sun 12/28/08	Thu 1/1/09
31	Prepare Product Design Review	1 day?	Fri 1/2/09	Fri 1/2/09



7

Design Project Proposal

Best System Concept Proposal

Proposal for Design of a Lunar Penetrator

submitted to Dr. John K. Gershenson

By Shashank Parasher

Department of Mechanical Engineering-Engineering Mechanics

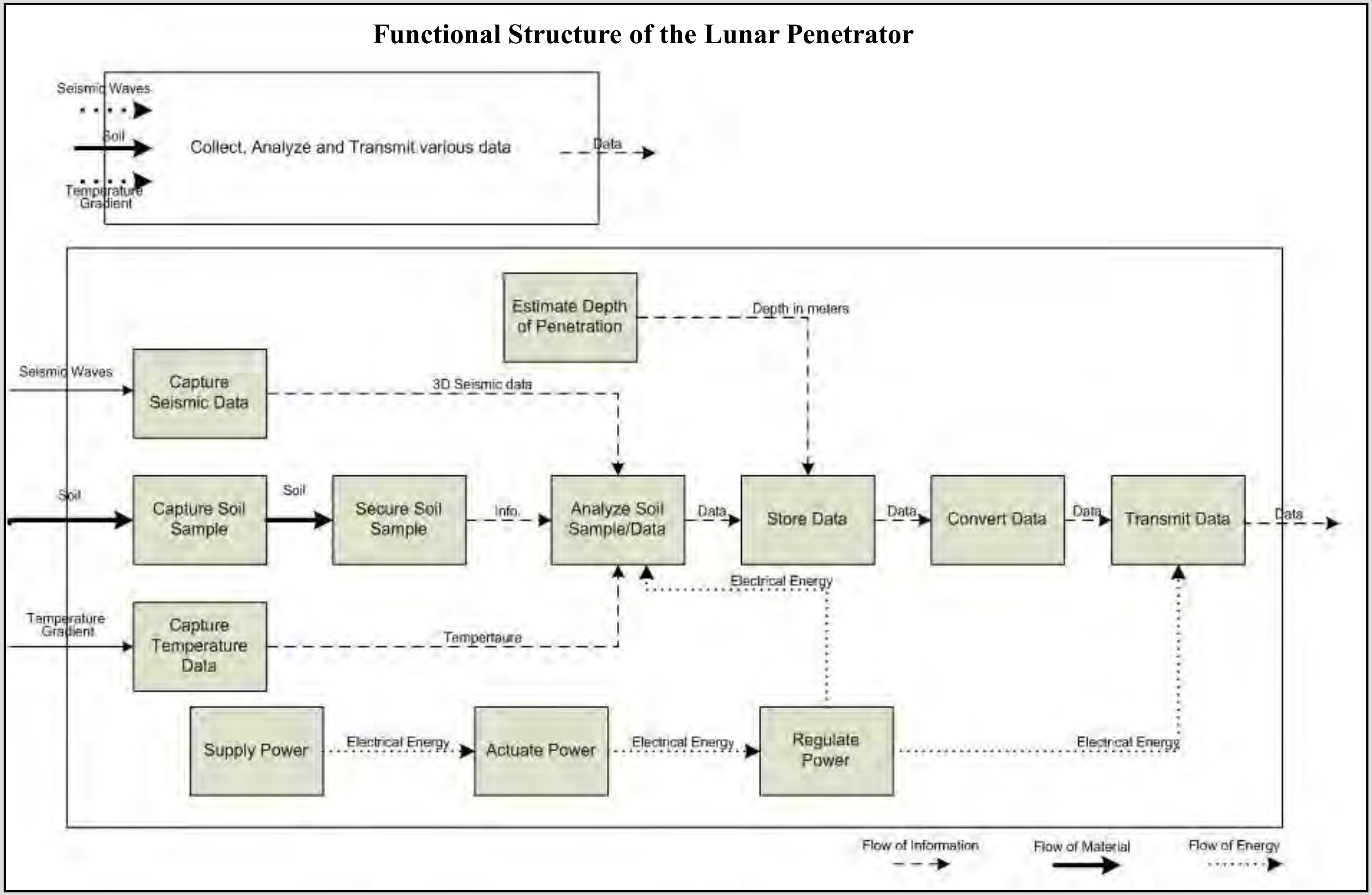
Michigan Technological University

Houghton MI

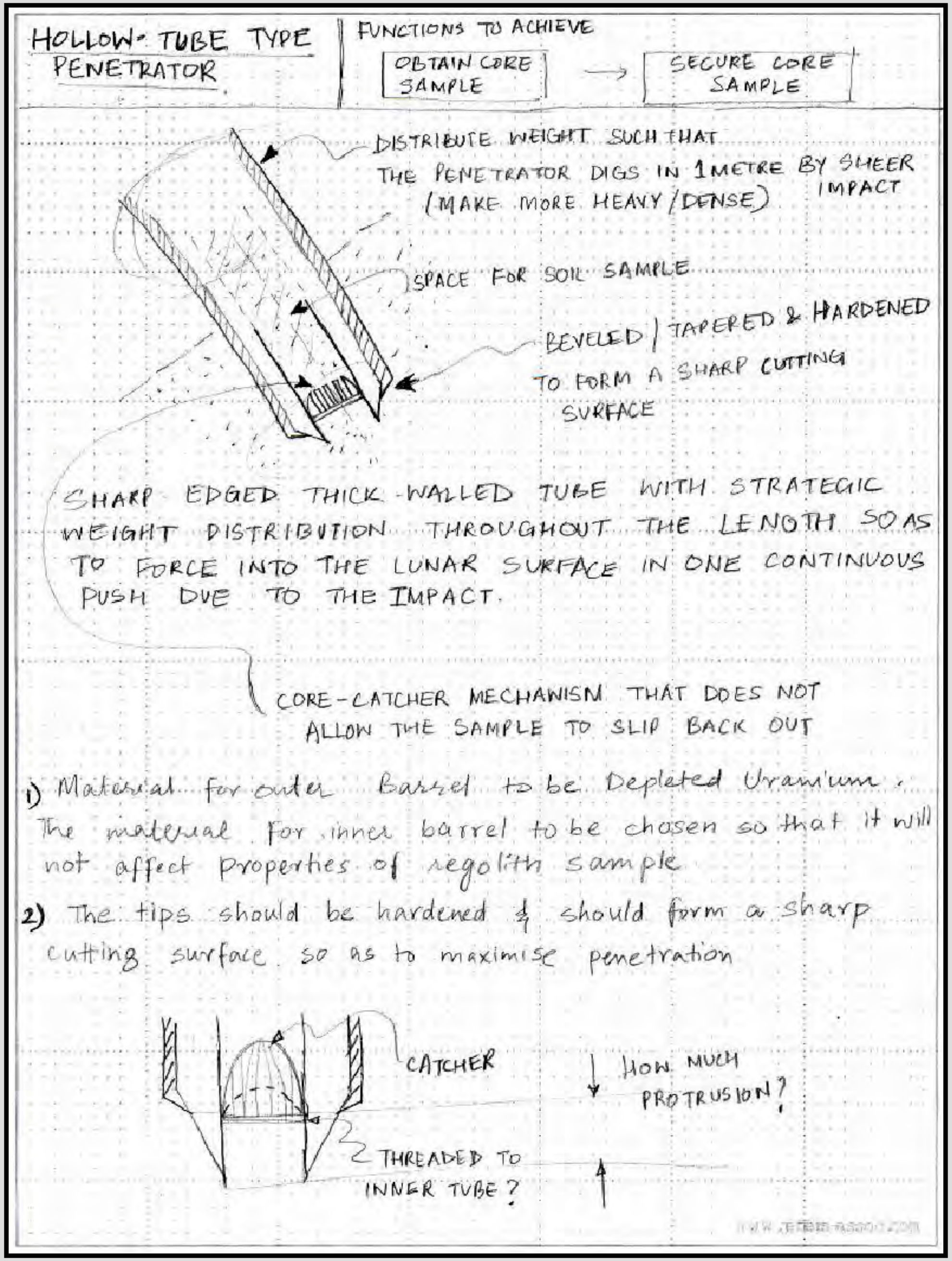
Date: 02/30/2009

Functional Descriptions and Concept Designs

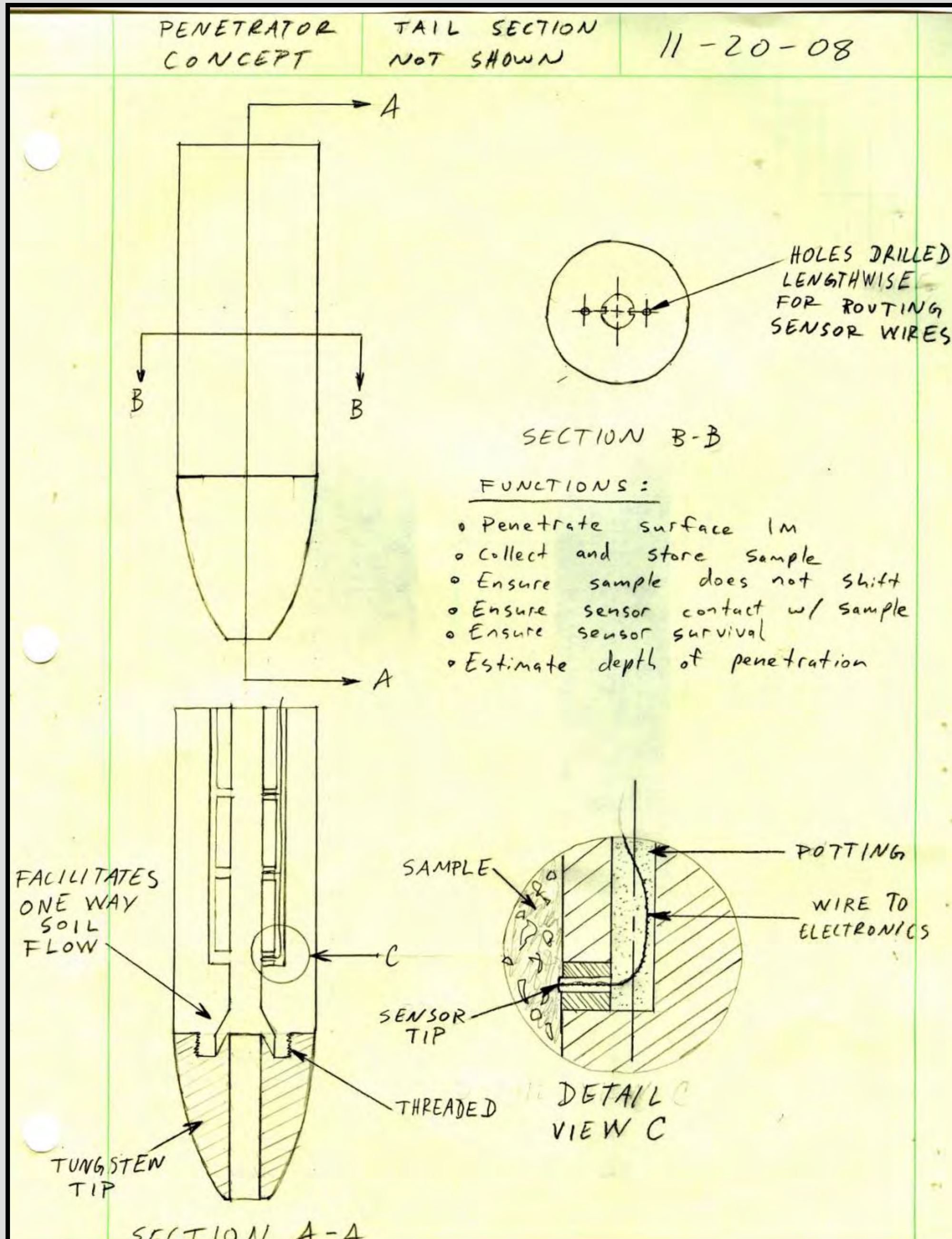
Functional Description



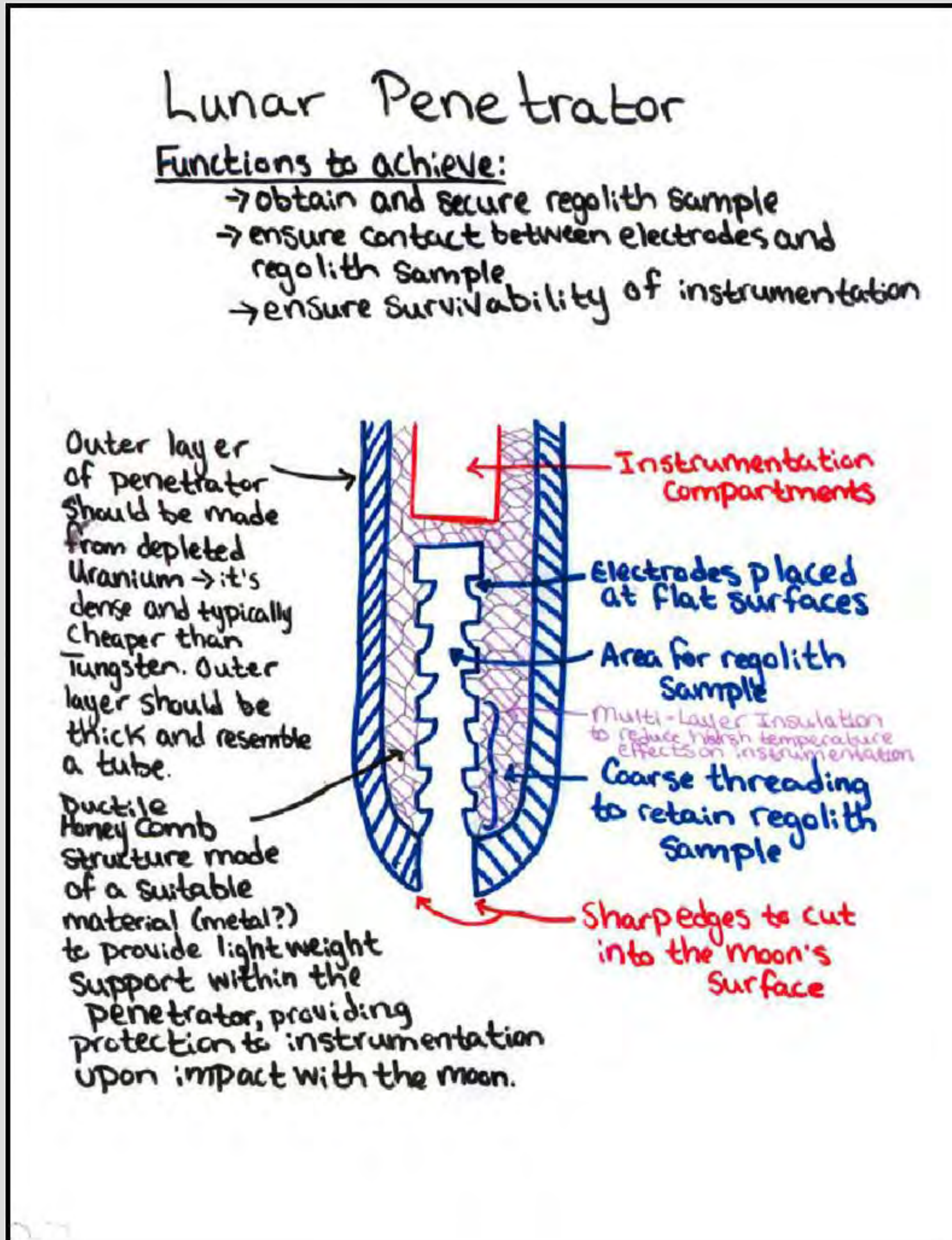
Lunar Penetrator Concept Drawing 1



Lunar Penetrator Concept Drawing 2



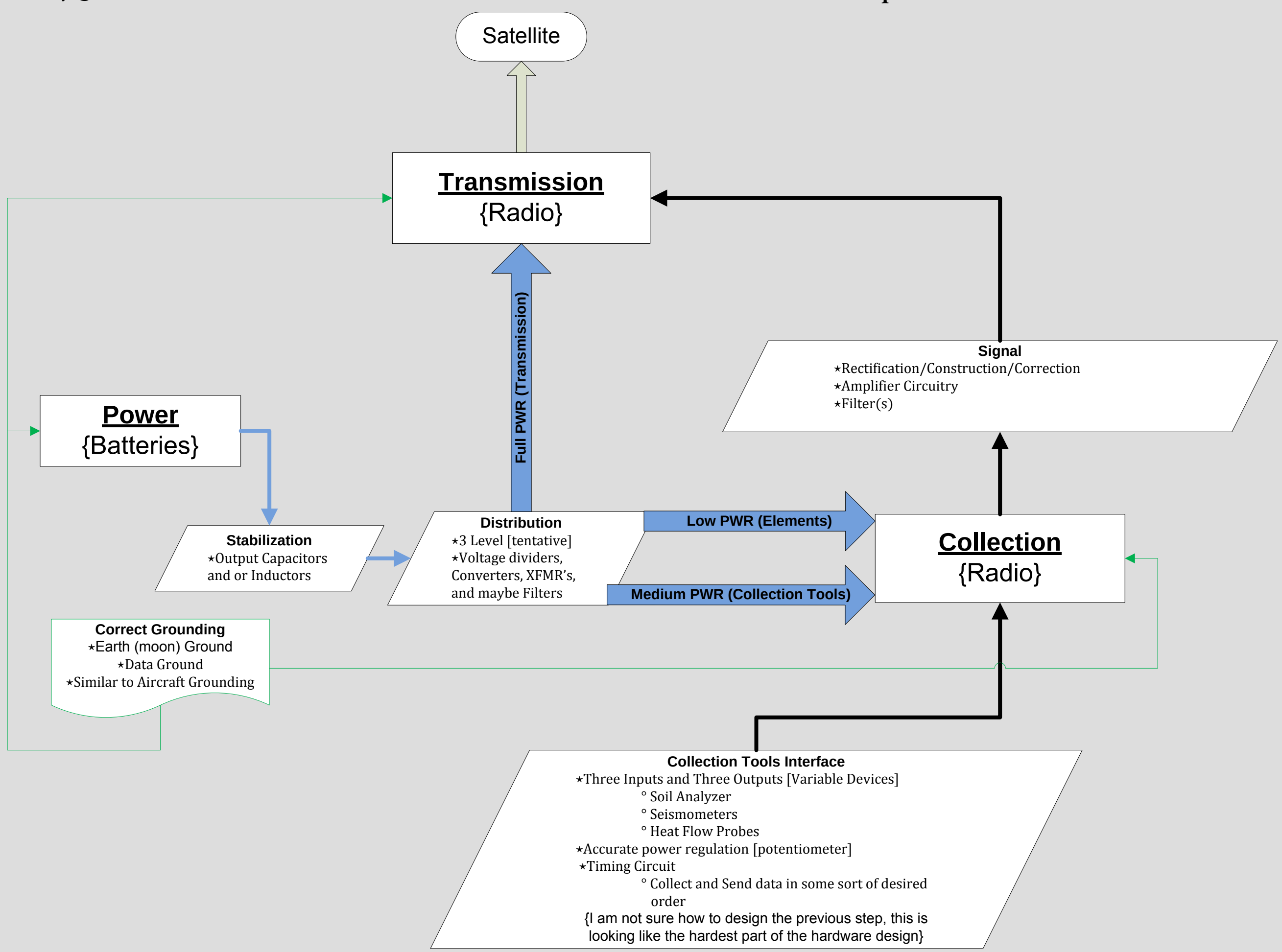
Lunar Penetrator Concept Drawing 3



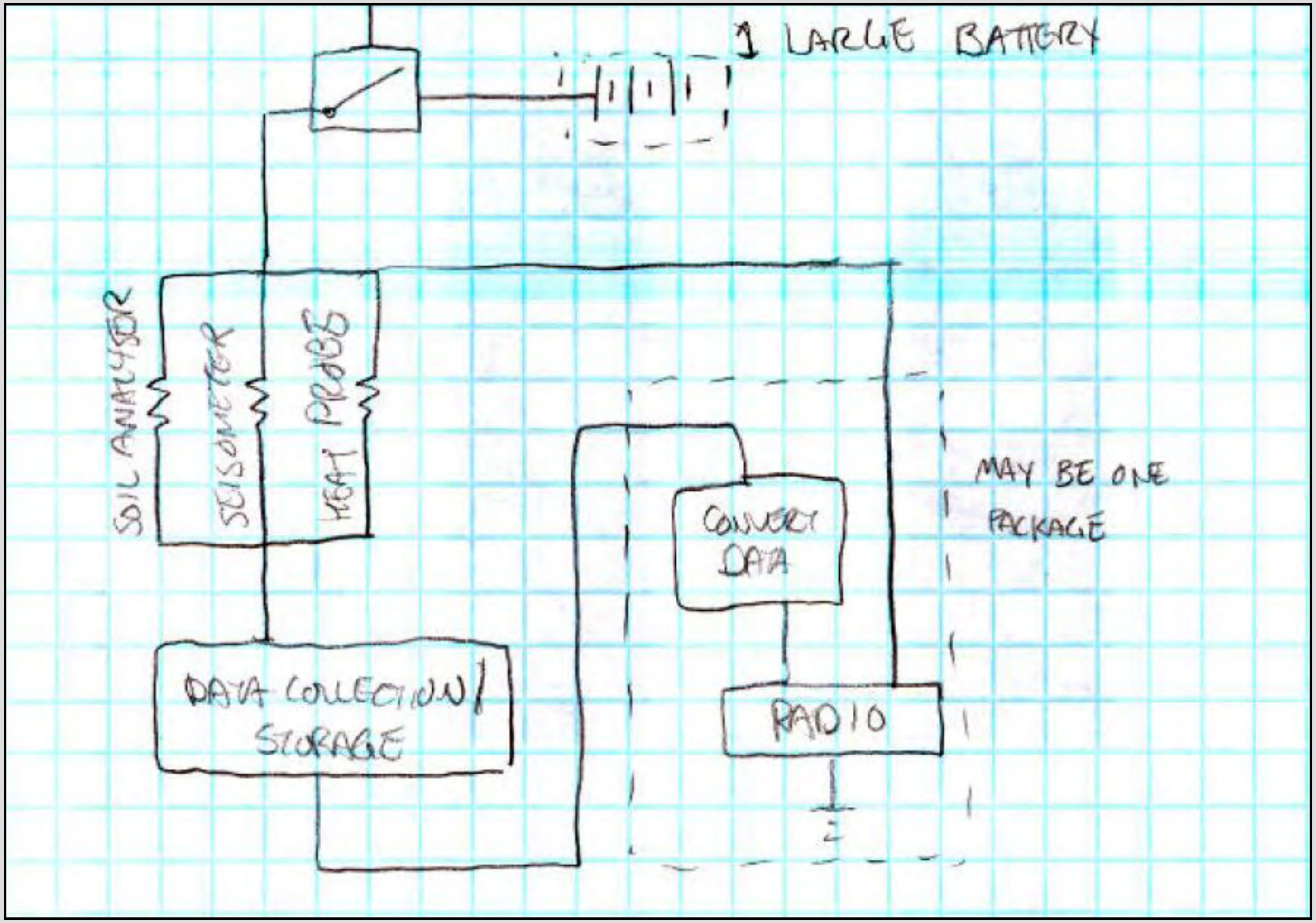
Electrical Concepts - Data Acquisition and Transmission

Christopher Boyd
ctboyd@mtu.edu

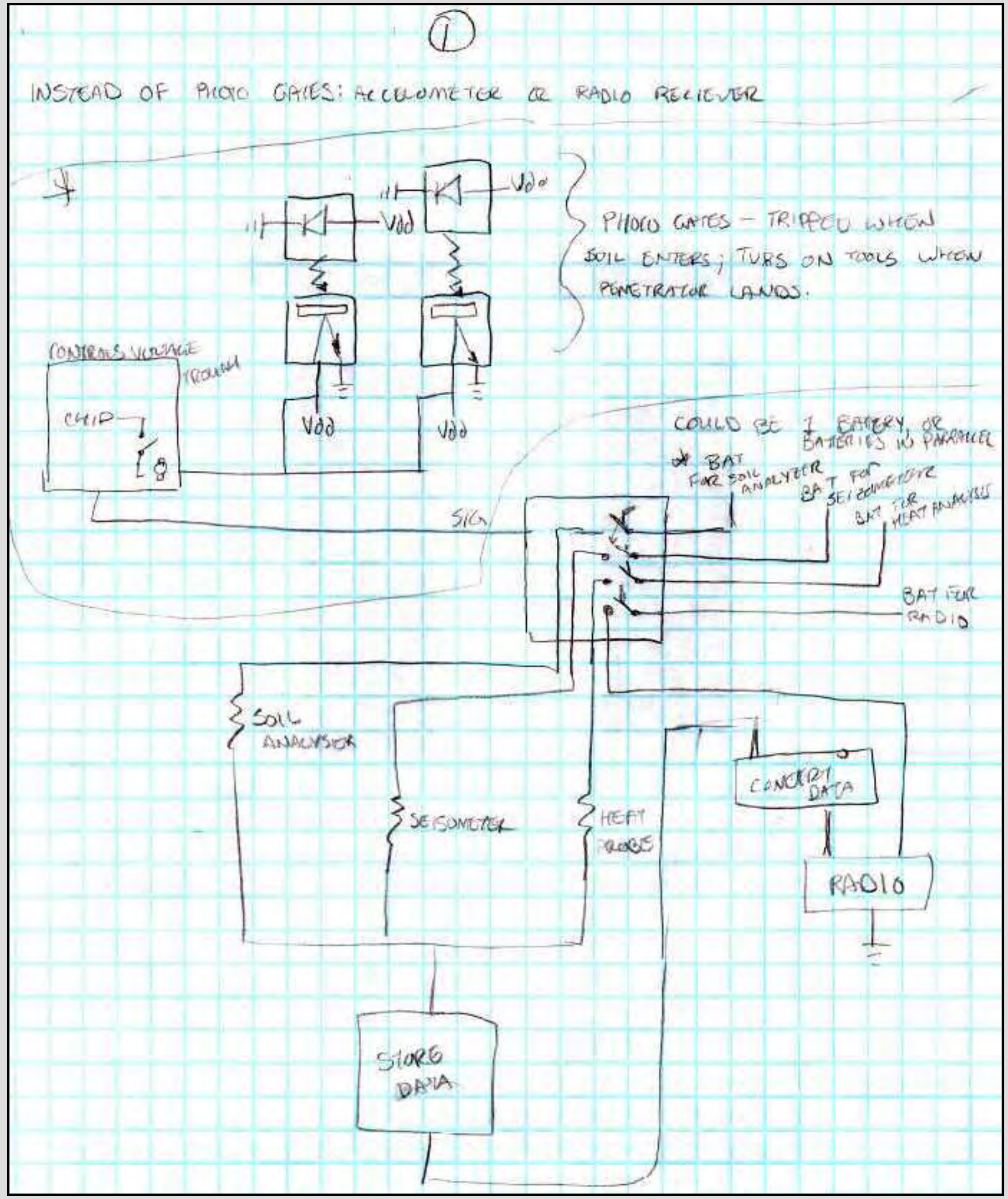
Data Acquisition and Transmission



Electrical Concepts - Batteries 1



Electrical Concepts - Batteries 2



Design Concept Keys

Design Concept Keys for Lunar Penetrator Concepts

Concepts	Design Concept Keys
Concept 1	Sharp edged thick walled tube, Core catcher mechanism, Tapered and hardened tips to form a sharp cutting edge, Twin barrel structure for main body
Concept 2	Tungsten tip threaded to core body, Inverted cone mechanism to retain sample, Special recesses to accommodate sensor wiring
Concept 3	Internal honeycomb structure, Internal threaded grooved cone to retain sample, Multi-layer insulation to protect instruments, Outward drilled holes through body
Data Acquisition and Transmission	Power stabilization setup, Three level distribution, Signal rectification and filtering, Radio grounding
Batteries 1	One large battery to power equipment like sensors and the radio equipment
Batteries 2	Photo gates for regulation, Batteries in parallel, Accelerometers for regulating soil sensing

Pugh Evaluation

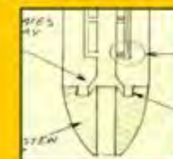
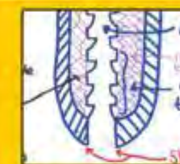
Pugh Evaluation

- Functions evaluated
  - Obtaining the core sample
  - Securing the core sample
  - Protection of instruments
  - Data collection
  - Radio transmission
  - Power supply

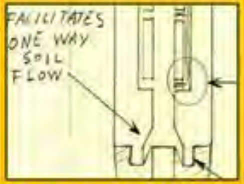
Pugh Evaluation - Round 1

- For the mechanical structure, Concept 1 was arbitrarily chosen as the datum
- Evaluation was carried out and Concept 3 proved to be superior compared to Concept 1
- Concept 3 was chosen as the new datum and concept 1 and 2 were improved for Round 2 of analysis

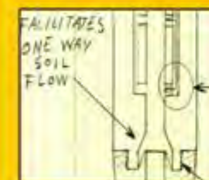
Pugh Evaluation – Obtaining Core Sample

		ALTERNATIVES		
	Function: Obtaining Core Sample	 Concept 1	 Concept 2	 Concept 3
S.No	Criteria	Rating	Rating	Rating
1	Reliability to obtain soil sample upon impact	+	+	+
2	Achievable penetration depth	-	S	+
3	Survival of impact	-	+	+
4	Few wearing parts	-	+	+
5	Few moving parts	-	+	+
6	Simplicity of manufacture	+	+	+
7	Ease of assembly	-	S	+
8	Moderate weight characteristics	-/S	S	S
9	Reliability to secure soil sample	+	S	+
10	Cost per variant	S	S	S
	Total +	3	4	8
	-	6	0	0

Pugh Evaluation – Securing Soil Sample

		ALTERNATIVES		
	Function: Securing Soil Sample	 Concept 1	 Concept 2	 Concept 3
	Criteria	Rating	Rating	Rating
S.No	Survival of impact	-	+	+
1	Few wearing parts	+	+	+
2	Few moving parts	-	+	+
3	Simplicity of manufacture	+	S	S
4	Ease of assembly	+	+	+
5	Reliability to secure soil sample	-	S	+
6	Cost per variant	+	-	S
	Total +	4	4	5
	-	3	1	0

Pugh Evaluation – Protection of Instruments

		ALTERNATIVES		
	Function: Protection of Instruments	 Concept 1	 Concept 2	 Concept 3
S.No	Criteria	Rating	Rating	Rating
1	Survival of impact	-	S	+
2	Few moving parts	-	+	+
3	Simplicity of manufacture	+	+	+
4	Ease of assembly	+	-	-
5	Moderate weight characteristics	-	S	+
6	Cost per variant	S	S	-
	Total +	2	2	4
	-	3	1	2

Pugh Evaluation – Radio/Transmission

		ALTERNATIVES		
	Function: Radio/Tranmission	Yaesu(Needs external modem)	Kenwood	Custom Designed
	Criteria	Rating	Rating	Rating
S.No	Survival of impact	+	+	+
1	Battery drain	S	S	S
2	Simplicity of manufacture	S	+	-
3	Ease of assembly	S	+	-
4	Moderate weight characteristics	S	S	S
5	Cost per variant	S	S	+
6	Safety characteristics	+	+	+
7	Uninterrupted data collection	+	+	S
8	Data transfer rate	+	+	S
9	Reliability to function	-	S	+
10	Temperature survival	S	S	S
11	Power efficiency	-	S	+
	Total +	4	6	5
	-	2	0	2

Pugh Evaluation – Power Supply

		ALTERNATIVES		
	Function: Power Supply	Individual battery for each function	Series and parallel combination	Single Large battery
	Criteria	Rating	Rating	Rating
S.No	Survival of impact	S	+	S
1	Battery drain	-	+	S
2	Simplicity of manufacture	S	S	-
3	Ease of assembly	S	S	+
4	Moderate weight characteristics	S	S	S
5	Cost per variant	+	+	-
6	Safety characteristics	S	S	S
7	Uninterrupted data collection	+	+	+
8	Reliability to power all devices	-	+	S
9	Reliability to function	-	S	+
10	Temperature survival	S	S	S
	Total +	1	5	3
	-	2	0	2

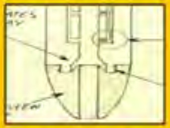
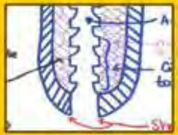
Pugh Evaluation – Data Collection

		ALTERNATIVES		
	Function: Data Collection	Microprocessor Based System	Basic Stamp	Custom Designed System
	Criteria	Rating	Rating	Rating
S.No	Survival of impact	-	-	+
1	Few wearing parts	-	S	+
2	Simplicity of manufacture	+	+	+
3	Ease of assembly	-	S	+
4	Moderate weight characteristics	-	+	+
5	Cost per variant	+	S	S
6	Safety characteristics	+	+	+
7	Uninterrupted data collection	S	S	S
8	Data transfer rate	+	S	+
9	Reliability to function	-	S	+
10	Temperature survival	+	+	+
11	Power efficiency	S	S	+
	Total +	5	4	10
	-	5	1	0

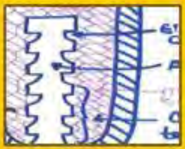
Pugh Evaluation - Round 2

- Weak Concepts 1 and 2, as well as Concept 3, were improved
- In Round 2 of Pugh analysis, Concepts 1 and 2 improved their score
- Concept 3 also improved its score
- Concept 3 was chosen as the ‗common goal' for the team

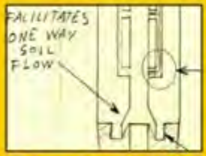
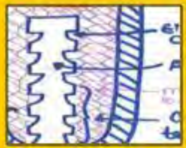
Round 2 Pugh Evaluation – Obtaining Core Sample

		ALTERNATIVES		
	Function: Obtaining Core Sample	 Concept 1	 Concept 2	 Concept 3
S.No	Criteria	Rating	Rating	Rating
1	Reliability to obtain soil sample upon impact	+	+	+
2	Achievable penetration depth	-	+	+
3	Survival of impact	-	+	+
4	Few wearing parts	-	-	+
5	Few moving parts	-	+	+
6	Simplicity of manufacture	+	+	+
7	Ease of assembly	-	-	+
8	Moderate weight characteristics	+	-	+
9	Reliability to secure soil sample	+	-	+
10	Cost per variant	-	-	S
	Total +	4	5	9
	-	6	5	0

Round 2 Pugh Evaluation – Securing Soil Sample

			ALTERNATIVES	
				
	Function: Securing Soil Sample	Concept 1	Concept 2	Concept 3
	Criteria	Rating	Rating	Rating
S.No	Survival of impact	-	+	+
1	Few wearing parts	+	+	+
2	Few moving parts	-	+	+
3	Simplicity of manufacture	+	-	+
4	Ease of assembly	+	+	+
5	Reliability to secure soil sample	-	-	+
6	Cost per variant	+	+	+
	Total +	4	5	7
	-	3	2	0

Round 2 Pugh Evaluation – Protection of Instruments

		ALTERNATIVES		
				
	Function: Protection of Instruments	**Concept 1**	**Concept 2**	**Concept 3**
S.No	**Criteria**	**Rating**	**Rating**	**Rating**
1	Survival of impact	**-**	**+**	**+**
2	Few moving parts	**-**	**-**	**+**
3	Simplicity of manufacture	**+**	**+**	**+**
4	Ease of assembly	**+**	**+**	**+**
5	Moderate weight characteristics	**+**	**-**	**+**
6	Cost per variant	**-**	**+**	**+**
	Total **+**	**3**	**4**	**6**
	-	**3**	**2**	**0**

Best System Concept Proposal

Updated Design Constraints

Updated Design Constraints for the Lunar Penetrator

Constraints	Method of Measurement	Target	Acceptable Limits
Impact angle	Angle [in degrees]	90°	80°-90°
Length of soil sample	Length of penetration [m]	1 m	1m
Location of impact	Particle size [μm]	50 μm	30- 100 μm
Mass of penetrator	Mass [kg]	<35 kg	<35kg
Length of penetrator	Length from tip to end of antenna [m]	< 2 m	< 2.5 m
Survive impact shock load	Impact force [G]	8000 G	>8000 G
Thermal constraints	Lowest endurable temperature	-55° C	-55° C
Data transmission	Date transfer rate [bits/sec]	9600 bits/sec	9,000 bits/sec - 10,000 bits/sec
Battery power	Capacity [Ah] needed to ensure functionality for specified lifetime	300 Ah	250-300 Ah
Cost	Cost of prototyping/ testing [$]	$4200	< $4500
Lifetime	Operational time	Regolith analysis: 1 transmission Other instruments: 1 year	Regolith analysis: >1 transmission Other instruments: >1 year
Accommodation of scientific payload	Capability of standard interfacing with scientific payload	Single interface	2-5 interfaces

Updated Design Objectives with Targets

Updated Design Objectives w/ targets for Lunar Penetrator

Design Objective	Weight	Design Estimation	Target
Low weight	10	Estimate the weight by volume of material in each part plus the weight of the payload	<35[kgs]
Low cost	10	Estimated total cost for prototyping and testing	<$4200
High strength and non corrosive material	20	Strength index	High impact strength
Space for accommodation of instruments *etc.*	10	Have at least A compartments of Φ50mm×50mm in height	A=3
Eliminate the risk of failure on impact due to movement of parts	20	N number of movable parts	N=0
To build an outer shell to protect payload from extreme temperature variations	10	Thermal resistance R	High thermal resistance
Adequate power supply by batteries	25	Capacity C	C = 300Ah
Lifetime of shell	5	Operating time t	t= 1 year

Design Decisions

Design Decisions for the Lunar Penetrator

Design decision	How alternatives will be identified and decisions made
1. Basic concept and form	Various different concept designs have been made with design concept keys. Well drawn sketches are analyzed using Pugh Analysis for different criteria.
2. Penetrator nose structure	Different nose shapes are identified. Impact loading characteristics for these are studied and decision made in the favor of the most robust 'truncated cone' shape that facilitates soil collection upon impact.
3. Internal profile	Internal profile to hold and retain soil sample. Various different profiles are studied and simulations done to find survivability of impact.
4. Payload vibration isolator	Impact analysis of various vibration isolation systems like, coil and spring, suspension, and foam *etc*. The best isolation system that is low cost and effective to be fitted.
5. Penetrator material	Materials evaluated for easy Machinability and impact strength. Choice to be made between depleted uranium and tungsten.
6. Payload insulation	Comparison of performance of commonly used insulation materials for outer space by using heat transfer simulation software.
7. Internal structure	Comparison of performance of solid chosen material or honeycomb structure for the interior of the penetrator. Evaluation done by noting impact characteristics using simulation software.

Updated Design Evaluation

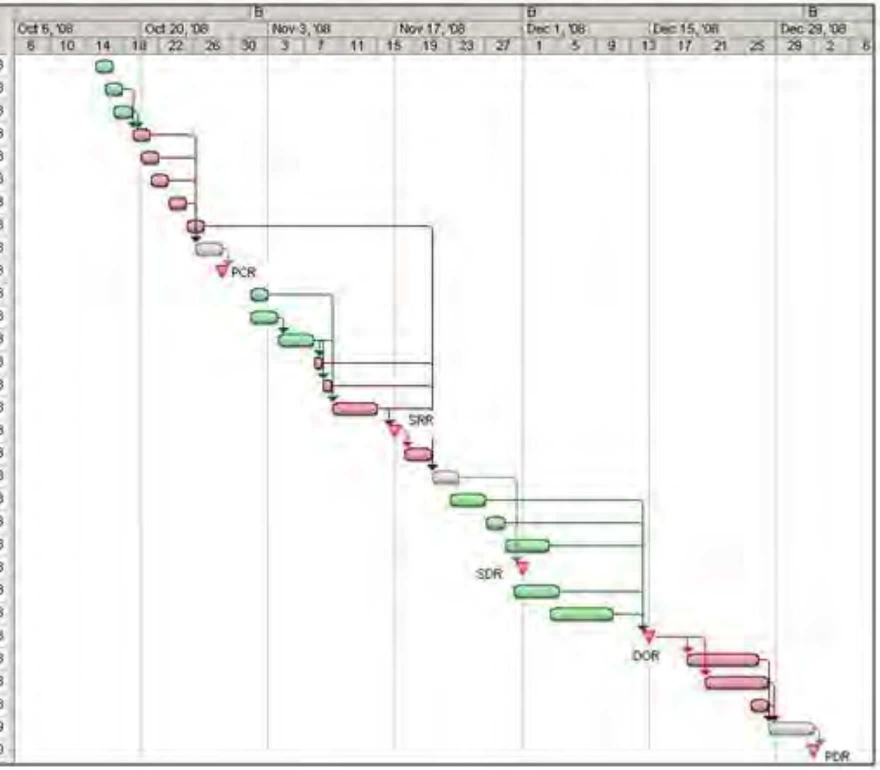
<u>**Updated Design Evaluation**</u>

- After the completion of the detailed design of the Lunar Penetrator, a subscale prototype will be fabricated. This prototype will be tested subject to successful completion of the Test Readiness Review by impacting it on surfaces that resemble the lunar surface and soil characteristics.
- The Lunar Penetrator design has been analytically evaluated using computer simulation methods like Finite Element Analysis during the conceptual design stage. The penetrator and its structure has to be further evaluated for high stresses and impact using better and more accurate software that can simulate the dynamic behavior of impact.
- The lunar penetrator will be fitted with vibration isolation devices like coil and springs, suspension, and foams. The response of these vibration isolation equipment has to be evaluates using simulation software to identify various vibration modes.
- Simulation of the electronic instrumentation on board the penetrator to be carried out using simulation software to program microprocessors and ensure successful operation.
- The design will be evaluated by external consultants.

Updated Project Plan

Updated Project Plan

	Task Name	Duration	Start	Finish
1	Identify User Requirements	2 days?	Wed 10/15/08	Thu 10/16/08
2	Set Design Objectives and Targets	2 days?	Thu 10/16/08	Fri 10/17/08
3	Conduct Trade-Off Analysis	2 days?	Fri 10/17/08	Sat 10/18/08
4	Write Project Analysis Statement	2 days?	Sun 10/19/08	Mon 10/20/08
5	Write Project Description	2 days?	Mon 10/20/08	Tue 10/21/08
6	Define Quantitative Design constraints	2 days?	Tue 10/21/08	Wed 10/22/08
7	Write Project Plan	2 days?	Thu 10/23/08	Fri 10/24/08
8	Write Design Evaluation Plan	2 days?	Sat 10/25/08	Sun 10/26/08
9	Develop Design Project Proposal	3 days?	Sun 10/26/08	Tue 10/28/08
10	Prepare Project Concept Review	1 day	Wed 10/29/08	Wed 10/29/08
11	Define Concept Benchmarks	2 days	Sat 11/1/08	Sun 11/2/08
12	Write Functional Descriptions	3 days	Sat 11/1/08	Mon 11/3/08
13	Create Concept Sketches	4 days	Tue 11/4/08	Fri 11/7/08
14	Write Design Concept Keys	1 day	Sat 11/8/08	Sat 11/8/08
15	Write Technology Readyness Assesment	1 day?	Sun 11/9/08	Sun 11/9/08
16	Prepare Pugh Evaluation	5 days	Mon 11/10/08	Fri 11/14/08
17	Prepare System Requirements Review	1 day?	Mon 11/17/08	Mon 11/17/08
18	Apply QFD	3 days	Tue 11/18/08	Thu 11/20/08
19	Write Best System Concept Proposal	3 days	Fri 11/21/08	Sun 11/23/08
20	Prepare Parameter Analysis	4 days	Sun 11/23/08	Wed 11/26/08
21	Prepare FMEA	2 days	Thu 11/27/08	Fri 11/28/08
22	Prepare Simulation	5 days	Sat 11/29/08	Wed 12/3/08
23	Write System Design Review	1 day?	Mon 12/1/08	Mon 12/1/08
24	Functional Testing	5 days?	Sun 11/30/08	Thu 12/4/08
25	Prepare DfX- Analysis	7 days?	Thu 12/4/08	Wed 12/10/08
26	Prepare Design Objectives Review	1 day?	Mon 12/15/08	Mon 12/15/08
27	Prepare Detailed Design Concept Drawings	6 days?	Fri 12/19/08	Fri 12/26/08
28	Prepare Construction/Assembly Drawings	7 days?	Sun 12/21/08	Sat 12/27/08
29	Write Bill of Materials	2 days	Fri 12/26/08	Sat 12/27/08
30	Write Parameter Level Design Proposal	5 days	Sun 12/28/08	Thu 1/1/09
31	Prepare Product Design Review	1 day?	Fri 1/2/09	Fri 1/2/09



Best System Concept Proposal

Best System Concept Proposal

Proposal for Design of a Lunar Penetrator

submitted to Dr. John K. Gershenson

By Shashank Parasher

Department of Mechanical Engineering-Engineering Mechanics

Michigan Technological University

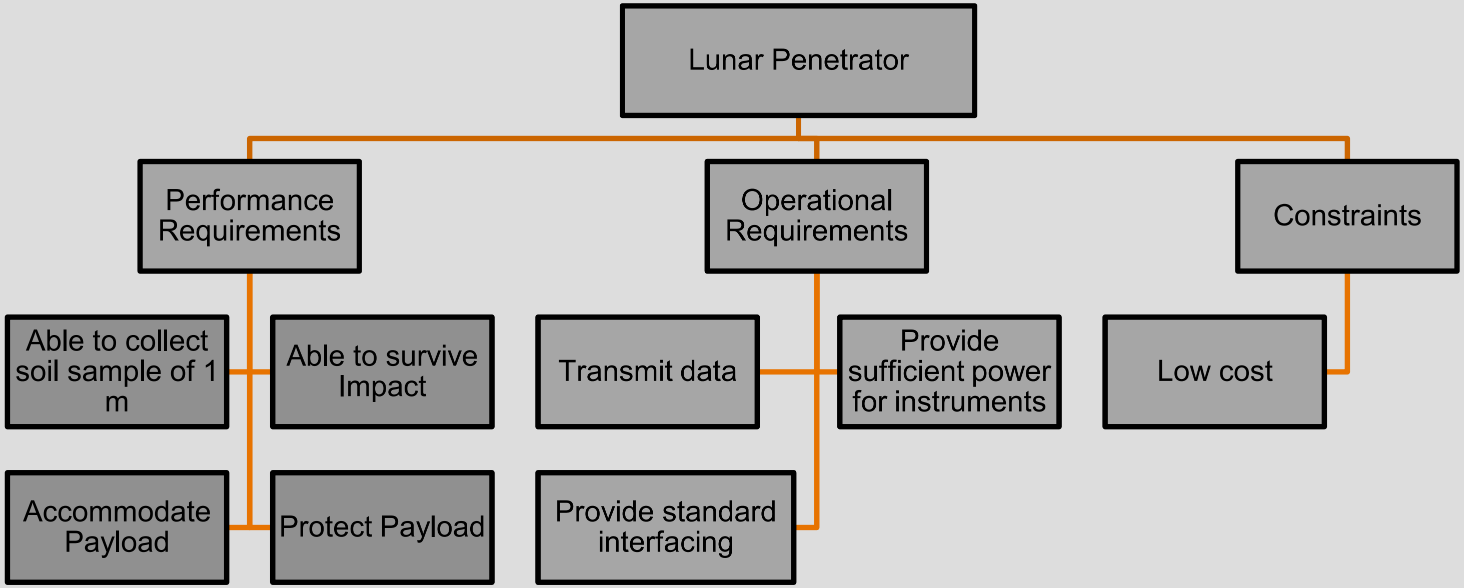
Houghton MI

Date: 02/30/2009

Quality Function Deployment (QFD)

QFD – Tree Diagram

- Customer requirements are identified using pre-phase A documents and forming Affinity and Tree Diagrams



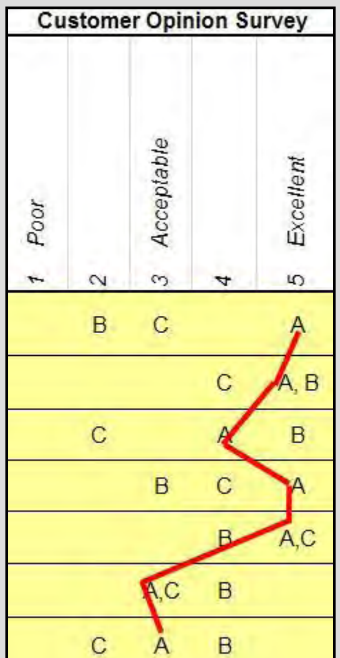
QFD – Requirement Weighting

- Weights are assigned to the requirements in agreement with the views of the customers

Customer Needs	Customer Weights
Able to collect 1m of soil sample	5
Survive impact	5
Accommodate payload	4
Protect payload	5
Transmit data	5
Provide sufficient power for instruments	3
Standard interfacing with data equipment	3

QFD – Customer Opinion Survey

- Quantify customer requirement priorities and perception of existing products and place on the right side of the house



Survey Legend	
A	Current product
B	Competitor B
C	Competitor C

QFD – Technical Requirements

- Voice of the company: describe product in terms of your design team using measurable characteristics

Technical Requirements							
Vibration isolation	Length of the penetrator	Shock load limit	Data transfer rate	Battery power	Number of connectors	Impact force	Angle of impact

QFD – Interrelationship Matrix

- Describe interrelationship between customer requirements and technical characteristics using symbols

		Technical Requirements							
Customer Needs	**Customer Weights**	Vibration isolation	Length of the penetrator	Shock load limit	Data transfer rate	Battery power	Number of connectors	Impact force	Angle of impact
Able to collect 1m of soil sample	5	▲	●					■	
Survive impact	5	●		●				●	●
Accommodate payload	4	▲	■			▲	●		
Protect payload	5	●		▲				■	
Transmit data	5				●	■			
Provide sufficient power for instruments	3				■	●			
Standard interfacing with data equipment	3						●		

Interrelationship Matrix Symbols	
●	Strong Interrelationship - 9
■	Moderate Interrelationship - 4
▲	Weak Interrelationship - 1

QFD - Roof

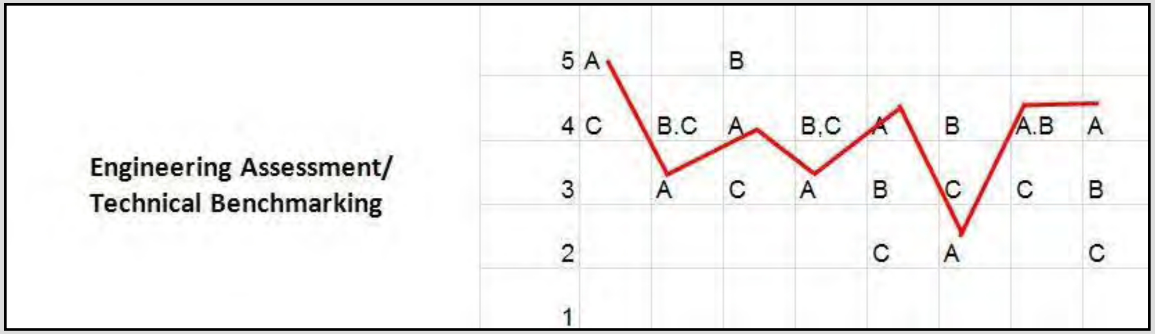
- Fill out the roof to find out where the technical requirements characterizing the product support or impede each other

	Vibration isolation	Length of the penetrator	Shock load limit	Data transfer rate	Battery power	Number of connectors	Impact force	Angle of impact
Length of the penetrator								
Shock load limit								
Data transfer rate								
Battery power	-	+		+				
Number of connectors			+					
Impact force	-		-	+				
Angle of impact		+		-			-	
Vibration isolation			-		+		-	

Technical Requirements

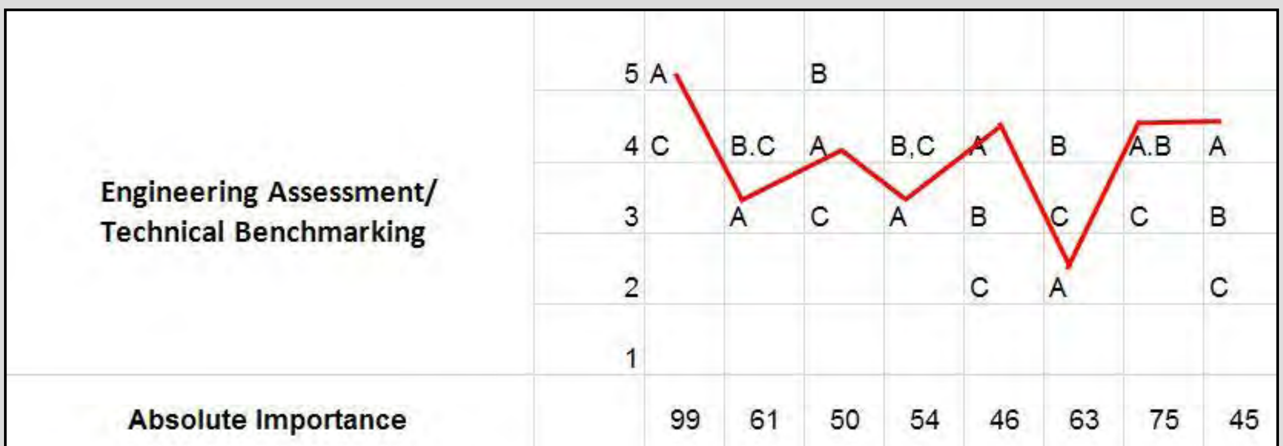
QFD – Technical Benchmarking

- Carry out technical benchmarking to find out relative technical position of existing product and determine target level of performance to be achieved by new product



QFD – Technical Priorities

- Fill bottom of the house by stating the technical priorities (absolute importance of each tech requirement in meeting needs)
- Multiply interrelationship points with customer weights for all technical requirements

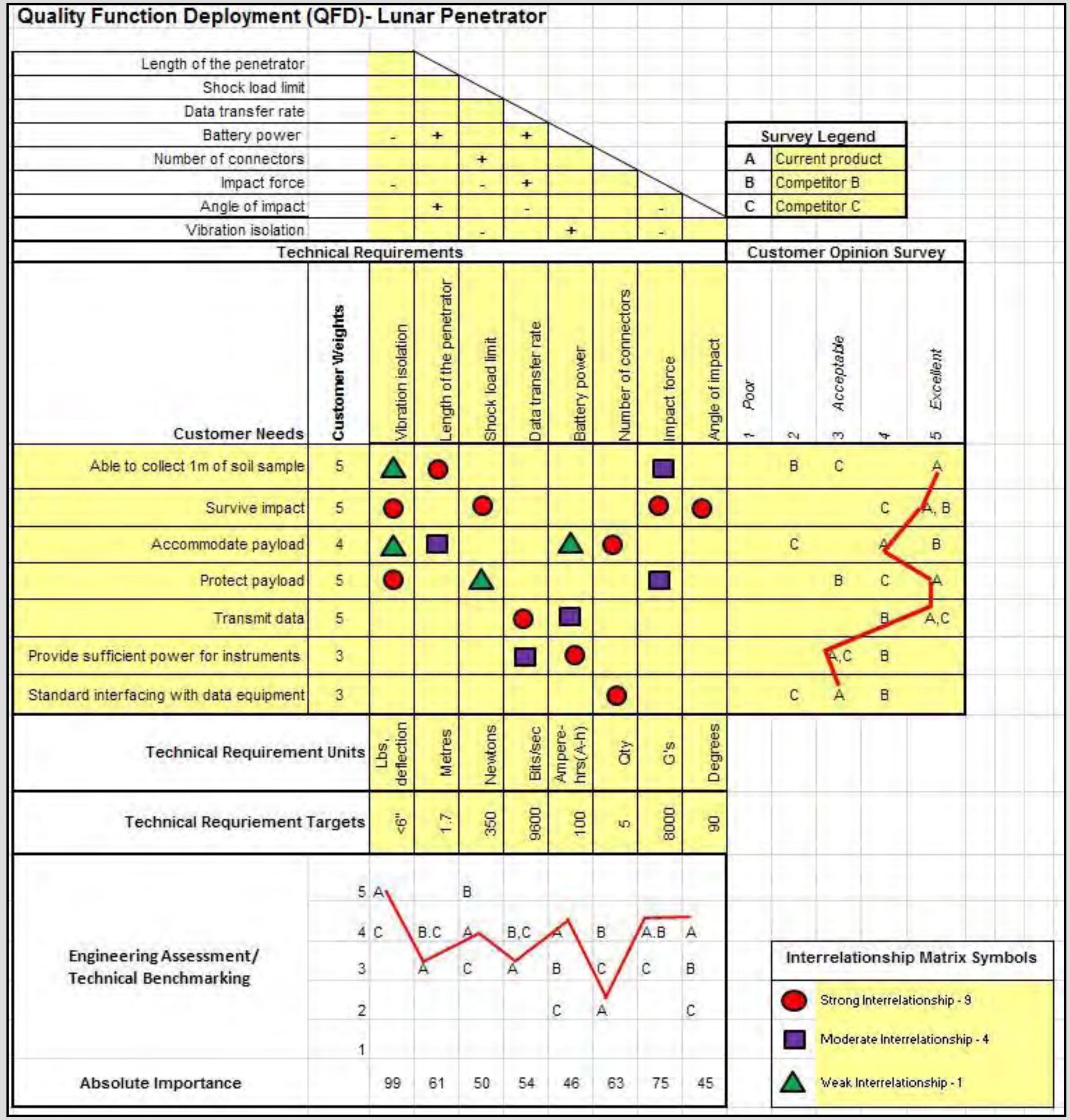


QFD – Engineering Target Values

- Set engineering target values to be met by new design

Technical Requirement Units	Lbs, deflection	Metres	Newtons	Bits/sec	Ampere-hrs(A-h)	Qty	G's	Degrees
Technical Requriement Targets	<6"	1.7	350	9600	100	5	8000	90

QFD- Lunar Penetrator



Failure Modes and Effects Analysis (FMEA)

FMEA - Identify Requirements and Functions

- Customer requirements and functions of the penetrator are identified using requirements document and QFD matrix

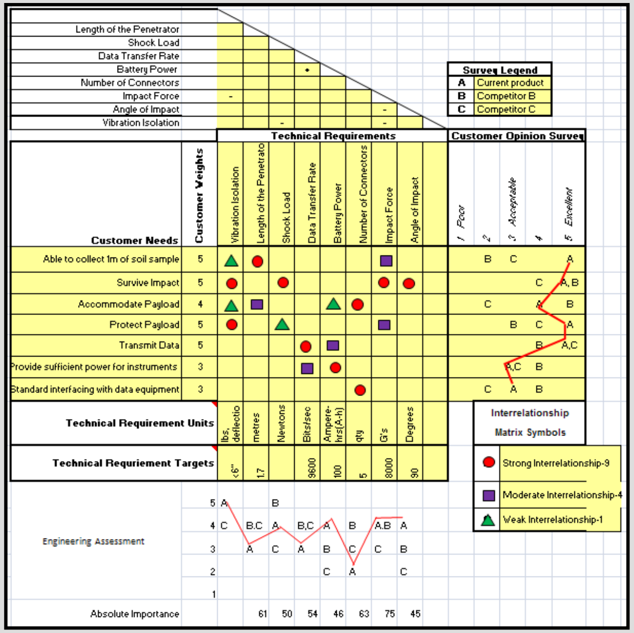
Project Concept Statement

Design of a Lunar Penetrator to collect one meter of regolith sample

Surface penetrators have been launched in the past by NASA space missions to Mars, which have failed to provide the intended outcome. According to the investigation results from the Mars mission, the failure is attributed to the inability of the communication system to transmit mission data to earth stations via the orbiting satellite. This may be due to the failure of the penetrator and communication hardware to survive impact.

The internal structure of the moon is still not well understood. Acquisition of further knowledge about the lunar core can help us to understand the moon's early history. The regolith sample can provide us with information on the presence of water and other organic volatiles which is relevant to assess lunar evolution and the possibility of future lunar resources. This reflects core interests of NASA's lunar missions which makes them the main sponsor for this project coordinating the primary design requirements and specifications.

Our main objective is to design and possibly test a sub scale prototype of the lunar penetrator which is able to demonstrate key attributes such as survival of great impact forces, compliance with weight and dimensional constraints, and the ability to interface with various scientific instruments. The objective will be achieved by following a structured design methodology, progressing from the Design problem analysis stage through the optimized parametric design stage. During this entire design process, various design tools will be used in order to achieve the desired objectives and minimize the risk of failure. Detailed design drawings and specifications will be delivered by March 2009, possibly followed by the fabrication of a subscale prototype.



FMEA - Order of Identification

- FMEA is carried out by identifying failure modes, causes, effects, detection, and recommended actions

Design FMEA- Lunar Penetrator											
Function or Requirement	Potential Failure Modes	Potential Causes of Failure	Occurrence	Local Effects	End Effects on Product, User, Other Systems	Severity	Detection Method/ Current Controls	Detection	RPN	Actions Recommended to Reduce RPN	Responsibility

FMEA - Measurement

- Points for Occurrence, Severity, and Detection are assigned according to a points system

Design FMEA- Lunar Penetrator

unction or equirement	Potential Failure Modes	Potential Causes of Failure	Occurrence	Local Effects	End Effects on Product, User, Other Systems	Severity	Detection Method/ Current Controls	Detection
t Im of soil e	No Soil Sample	Improper angle of attack	8	Penetrator hits surface at wrong angle	Inability to collect any data	8	Navigation controls	4
		Inability to penetrate	7	No soil sample collected	Inability to collect any data	8	Sensor data	9
		Malfunction or fracture of serrated profile	5	No soil sample collected	Inability to collect any data	6	Sensor data	9
	Less Soil Sample	Collapse of internal structure	9	Soil not able to pentrate fully	Insufficient/no data	6	Sensor data	9
		Fracture of serrated profile	7	Soil not able to pentrate fully	Insufficient/no data	7	Sensor data	9

Criteria	Ranking
Minor nature of failure, no noticeable effect on performance, undetectable by customer.	1
Low severity, causing only slight customer annoyance due to very minor subsystem performance degradation.	2 – 3
Moderate failure causing some customer discomfort, dissatisfaction, and annoyance due to subsystem or total performance degradation.	4 – 6
High degree of customer dissatisfaction due to nature of the failure (inoperable subsystem or total system).	7 – 8
Very high severity ranking for failure mode involving potential safety problems and/or nonconformance to federal regulations. Nonregulated components with a 9 or 10 severity ranking and occurrence rankings > 1 should be designated as control items (♦).	9 – 10

Criteria	Ranking	Probability
Remote likelihood that product would be shipped containing such an obvious defect, since it is detected by subsequent factory operations.	1	1/10,000
Low likelihood for shipment with defect which is visually obvious or has 100% automatic checking.	2 3 4 5	1/5,000 1/2,000 1/1,000 1/500
Moderate likelihood for shipment with defect, since the defect is easily identifiable through automatic inspection or functional checking.	6 7 8	1/200 1/100 1/50
High likelihood of shipping with subtle defect.	9	1/20
Very high likelihood that defect will not be detected prior to shipping or sale (checks are impossible or defect is latent).	10	1–1/10

FMEA- RPN

- RPN is calculated and the entire process is tabulated in the prescribed format

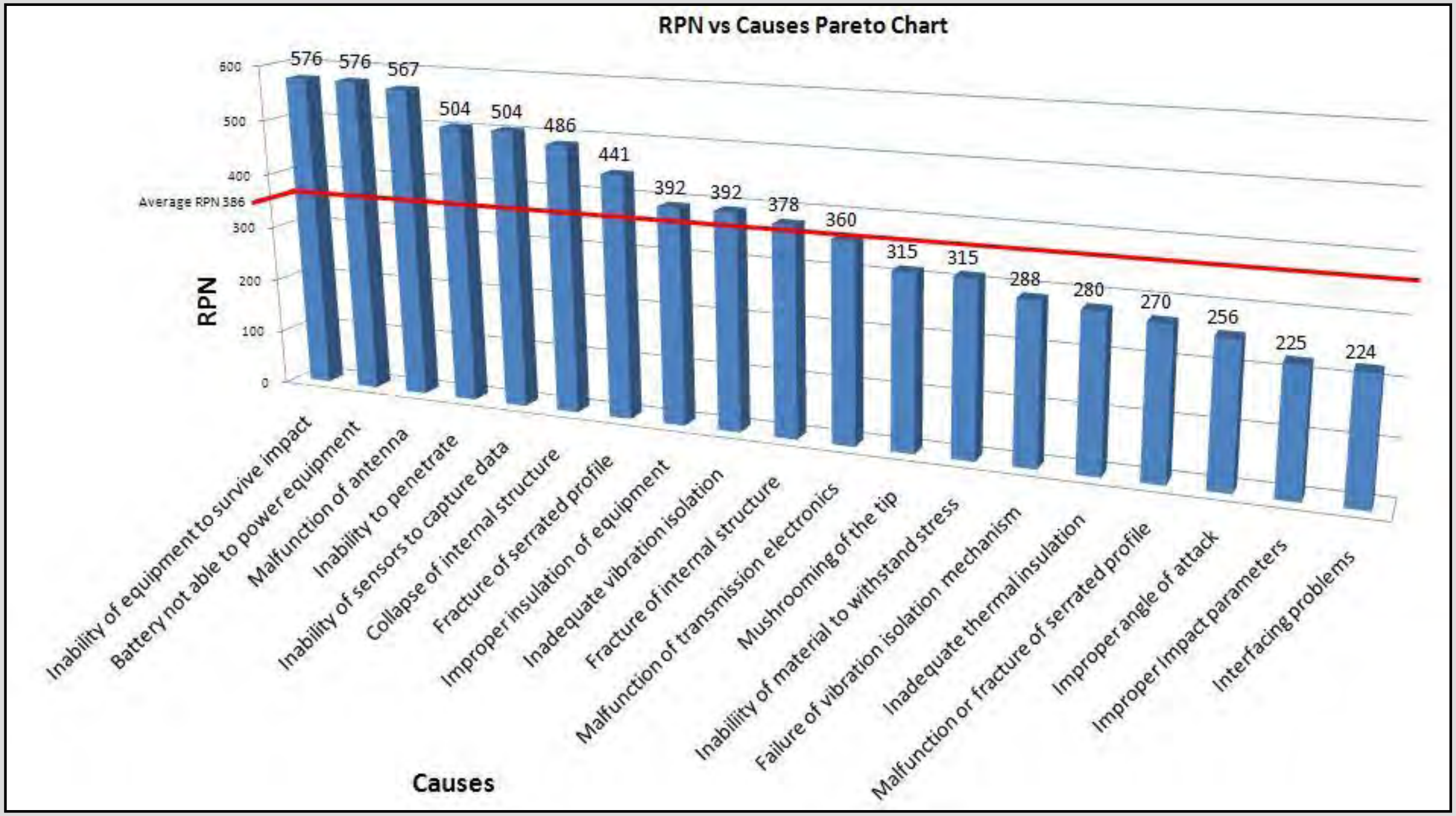
Lunar Penetrator					
Effects on duct, User, er Systems	Severity	Detection Method/ Current Controls	Detection	RPN	
lity to collect any data	8	Navigation controls	4	256	A
lity to collect any data	8	Sensor data	9	504	E
lity to collect any data	6	Sensor data	9	270	
ficient/no data	6	Sensor data	9	486	
ficient/no data	7	Sensor data	9	441	
penetration/no data	7	Sensor data	9	315	E
ficient/no data	6	Sensor data	9	378	
oil collection	5	Sensor data	9	315	
netration and il collection	5	Sensor Data	9	225	E

FMEA - Lunar Penetrator

Design FMEA- Lunar Penetrator

Function or Requirement	Potential Failure Modes	Potential Causes of Failure	Occurrence	Local Effects	End Effects on Product, User, Other Systems	Severity	Detection Method/ Current Controls	Detection	RPN	Actions Recommended to Reduce RPN	Responsibility
Collect Im of soil sample	No Soil Sample	Improper angle of attack	8	Penetrator hits surface at wrong angle	Inability to collect any data	8	Navigation controls	4	256	Accurate Nvigation System	Mechanical Design Team
		Inability to penetrate	7	No soil sample collected	Inability to collect any data	8	Sensor data	9	504	Better nose design and navigation systems	Mechanical Design Team
		Malfunction or fracture of serrated profile	5	No soil sample collected	Inability to collect any data	6	Sensor data	9	270	Stress analysis and materials selection	Mechanical Design Team
	Less Soil Sample	Collapse of internal structure	9	Soil not able to pentrate fully	Insufficient/no data	6	Sensor data	9	486	Stress analysis and materials selection	Mechanical Design Team
		Fracture of serrated profile	7	Soil not able to pentrate fully	Insufficient/no data	7	Sensor data	9	441	Design robust serrated profile	Mechanical Design Team
Survive Impact	Fracture of structure	Mushrooming of the tip	5	Tip mushrooms causing extensive structural damage	Less penetration/no data	7	Sensor data	9	315	Better nose design wrt impact force and materials	Mechanical Design Team
		Fracture of internal structure	7	Soil not able to pentrate fully	Insufficient/no data	6	Sensor data	9	378	Stress analysis and materials selection	Mechanical Design Team
		Inabiliity of material to withstand stress	7	Fracture of material	No soil collection	5	Sensor data	9	315	Non destructive testing and FEA simulations	Mechanical Design Team
		Improper Impact parameters	5	Wrong angle of imapct leads to bad survival rate	No penetration and no sil collection	5	Sensor Data	9	225	Better nose design and navigation systems	Mechanical Design Team
Transmit data	No data (transmitted)	Malfunction of transmission electronics	5	No data captured from the sensors	No useful data collected and transmitted	8	Transmitted Data	9	360	High quality and robust electronics	Electrical Design Team
		Malfunction of antenna	7	No data transmitted	No useful data collected and transmitted	9	Transmitted Data	9	567	Design appropraite sized robust antenna	Electrical Design Team
		Inability of equipment to survive impact	8	Bad equipment functionality	No useful data collected and transmitted	9	Collected and transmitted data	8	576	Provide vibration isolation to equipment	Mechanical Design Team
		Battery not able to power equipment	8	No supply of power to equipment	Inadequate/no equipment functionality	9	Collected and transmitted data	8	576	Design battery for adequate operation	Electrical Design Team
		Inability of sensors to capture data	7	No/bad data for transmission	No useful data collected and transmitted	9	Collected and transmitted data	8	504	Use robust sensors and provide vibration isolation	Electrical Design Team
		Interfacing problems	4	Data not transferred from sensors to transmission equipment	No useful data collected and transmitted	7	Collected and transmitted data	8	224	Robust and complimenting interfacing solutions	Electrical Design Team
Withstand temperatures	Inability (to withstand)	Improper insulation of equipment	7	Melting of electronics	No useful data collected and transmitted	7	Collected and transmitted data	8	392	Provide adequate insulation	Mechanical and Electrical Design Team
Payload Protection	Destruction of payload	Inadequate vibration isolation	7	Impact transferred to payload	Payload damaged	7	Collected and transmitted data	8	392	Provide vibration isolation/ damping	Mechanical Design Team
		Failure of vibration isolation mechanism	6	Impact transferred to payload	Payload damaged	6	Collected and transmitted data	8	288	Better design and simulation of chosen damping solutions	Mechanical and Electrical Design Team
		Inadequate thermal insulation	5	Thermal loads transferred to payload	Payload damaged	7	Collected and transmitted data	8	280	Provide adequate insulation	Mechanical Design Team

Pareto to Find Frequently Occurring Modes



FMEA – Preventive Design Solutions

- Frequently occurring modes are identified and design solutions to eliminate the modes are found
- For example, nose design is improved to avoid ‗mushrooming effect'
- Damping is provided using coil springs to protect payload from impact

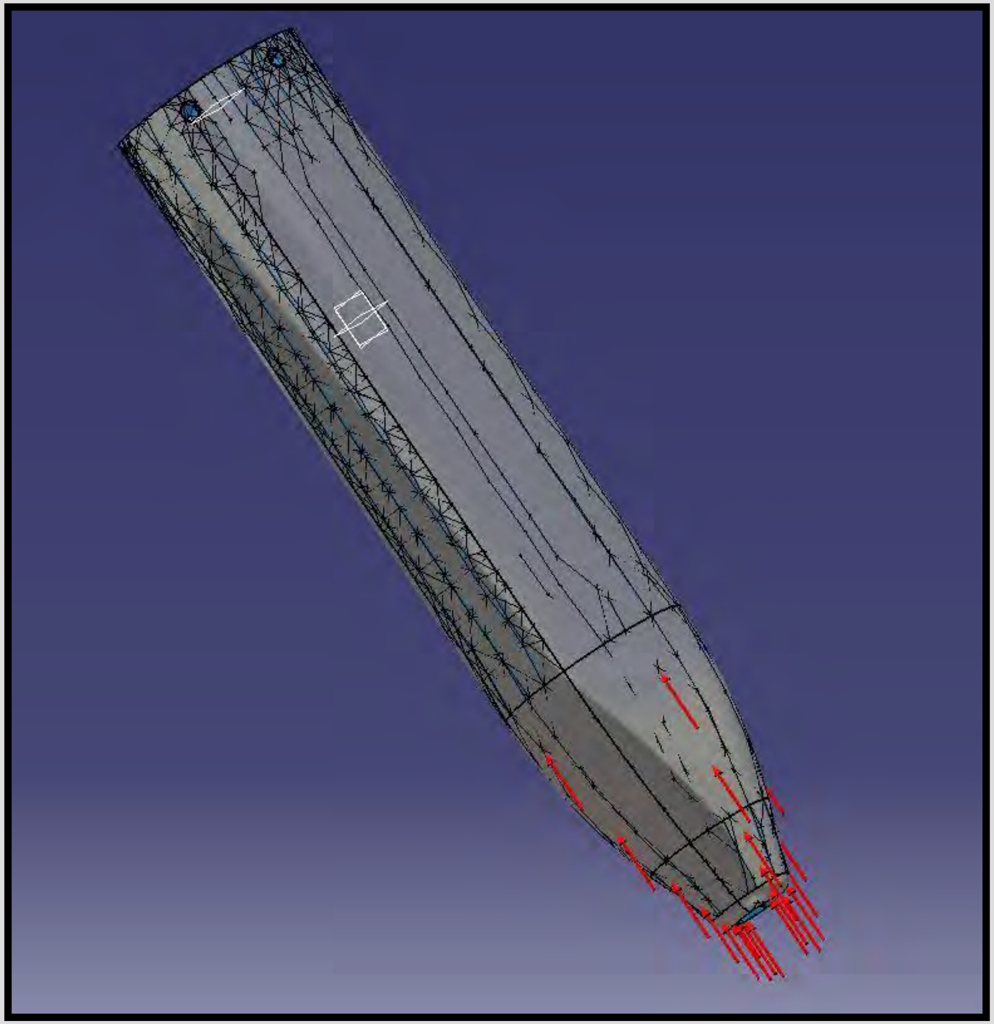
Actions Recommended to Reduce RPN	Responsibility
Accurate Nvigation System	Mechanical Design Team
Better nose design and navigation systems	Mechanical Design Team
Stress analysis and materials selection	Mechanical Design Team
Stress analysis and materials selection	Mechanical Design Team
Design robust serrated profile	Mechanical Design Team
Better nose design wrt impact force and materials	Mechanical Design Team
Stress analysis and materials selection	Mechanical Design Team

Structural Analysis and Simulation

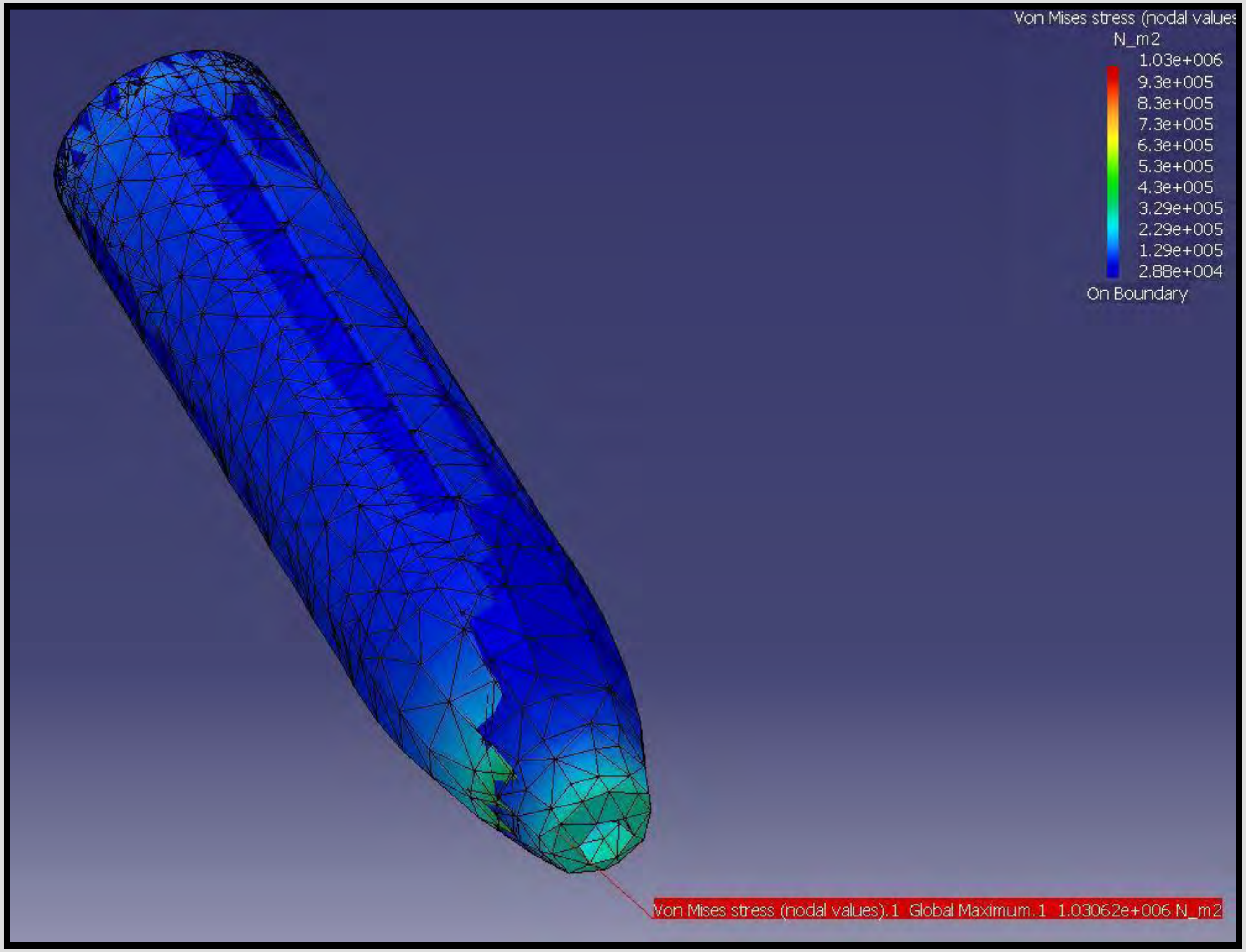
Case 1 – Vertical Loading

- The penetrator was evaluated for vertical loading
- A model of the penetrator is created using modeling software
- The model is constrained and loads applied to identify stress, displacement, and deformation characteristics

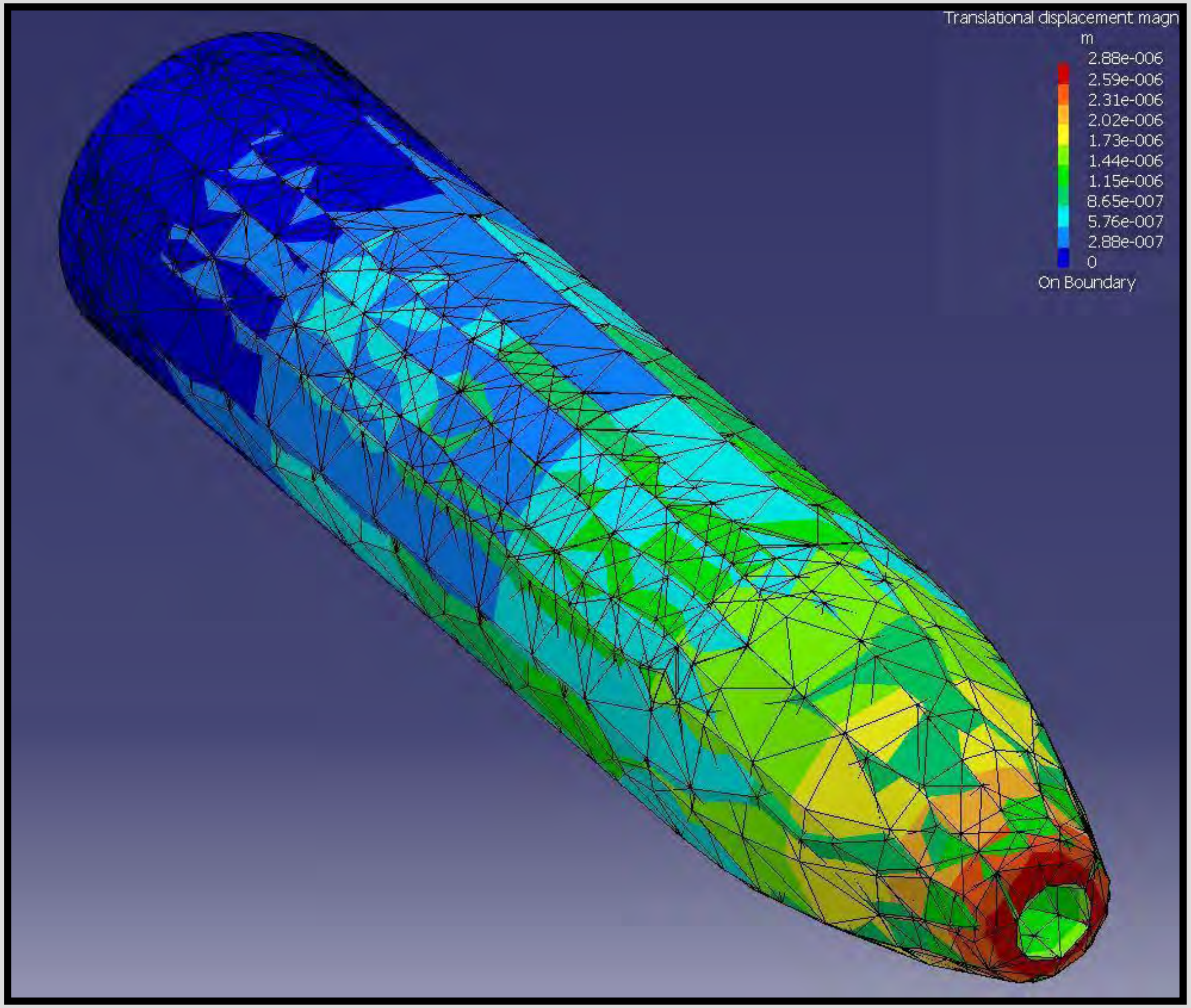
Vertical Loading



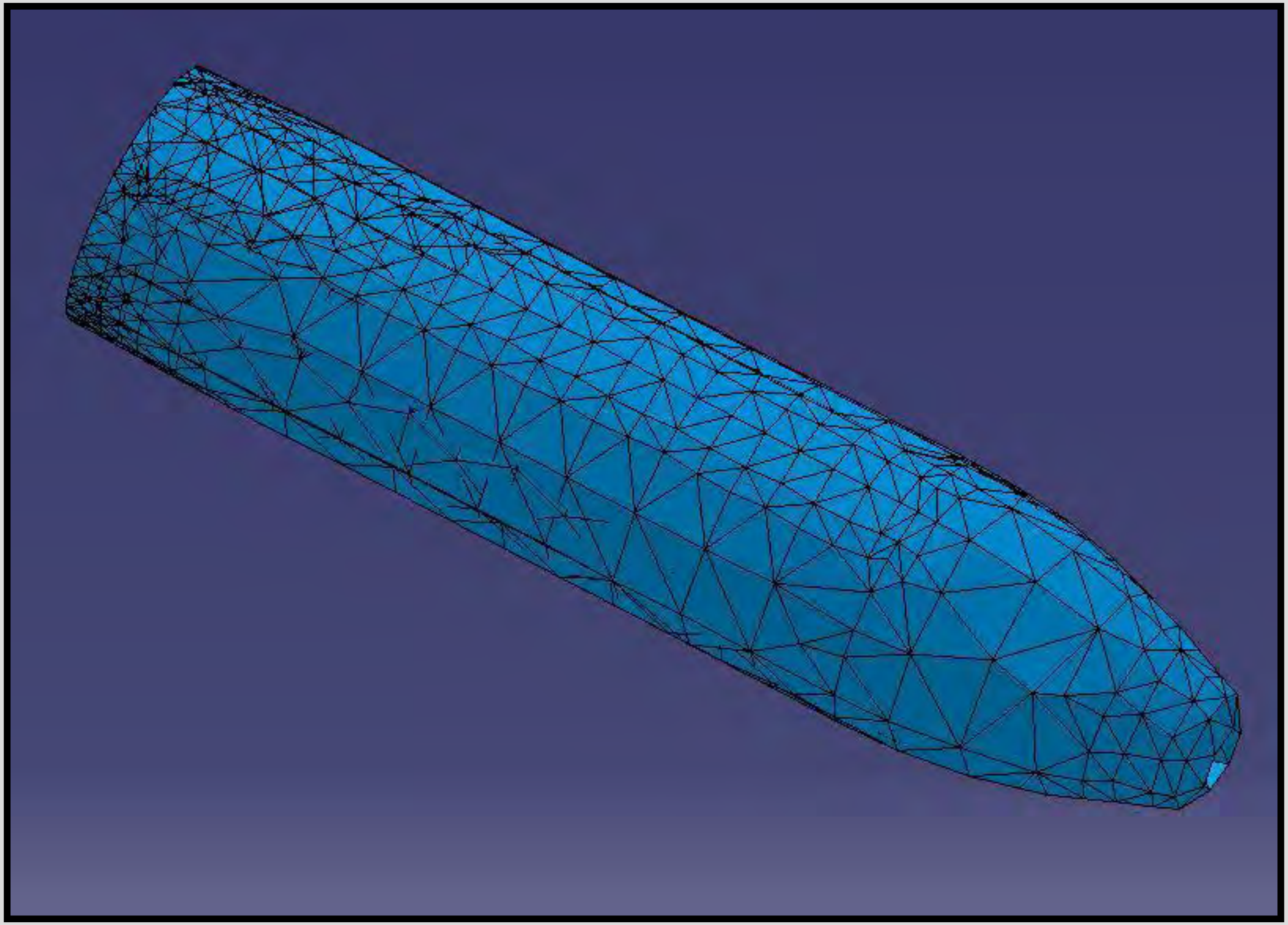
Von Mises Stress (nodal values)



Translational Displacement Magnitude



Deformation Characteristics



Quantitative Results

Vertical Loading Analysis

MESH:

Entity	Size
Nodes	5390
Elements	24792

ELEMENT TYPE:

Connectivity	Statistics
TE4	24792 (100.00%)

ELEMENT QUALITY:

Criterion	Good	Poor	Bad	Worst	Average
Stretch	24567 (99.09%)	225 (0.91%)	0 (0.00%)	0.212	0.591
Aspect Ratio	24572 (99.11%)	220 (0.89%)	0 (0.00%)	9.059	2.106

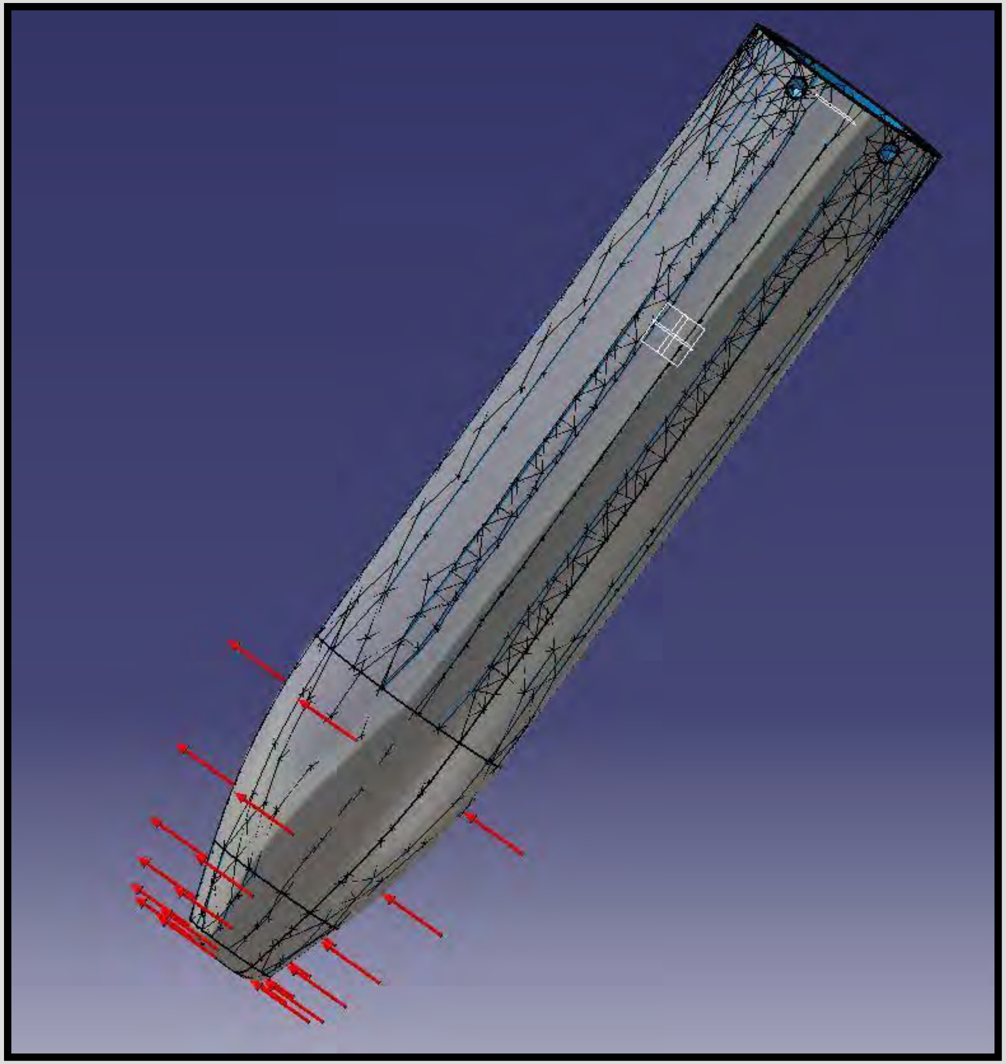
Materials.1

Material	Tungsten
Young's modulus	4e+011N_m2
Poisson's ratio	0.31
Density	16870kg_m3
Coefficient of thermal expansion	5.58e-006_Kdeg

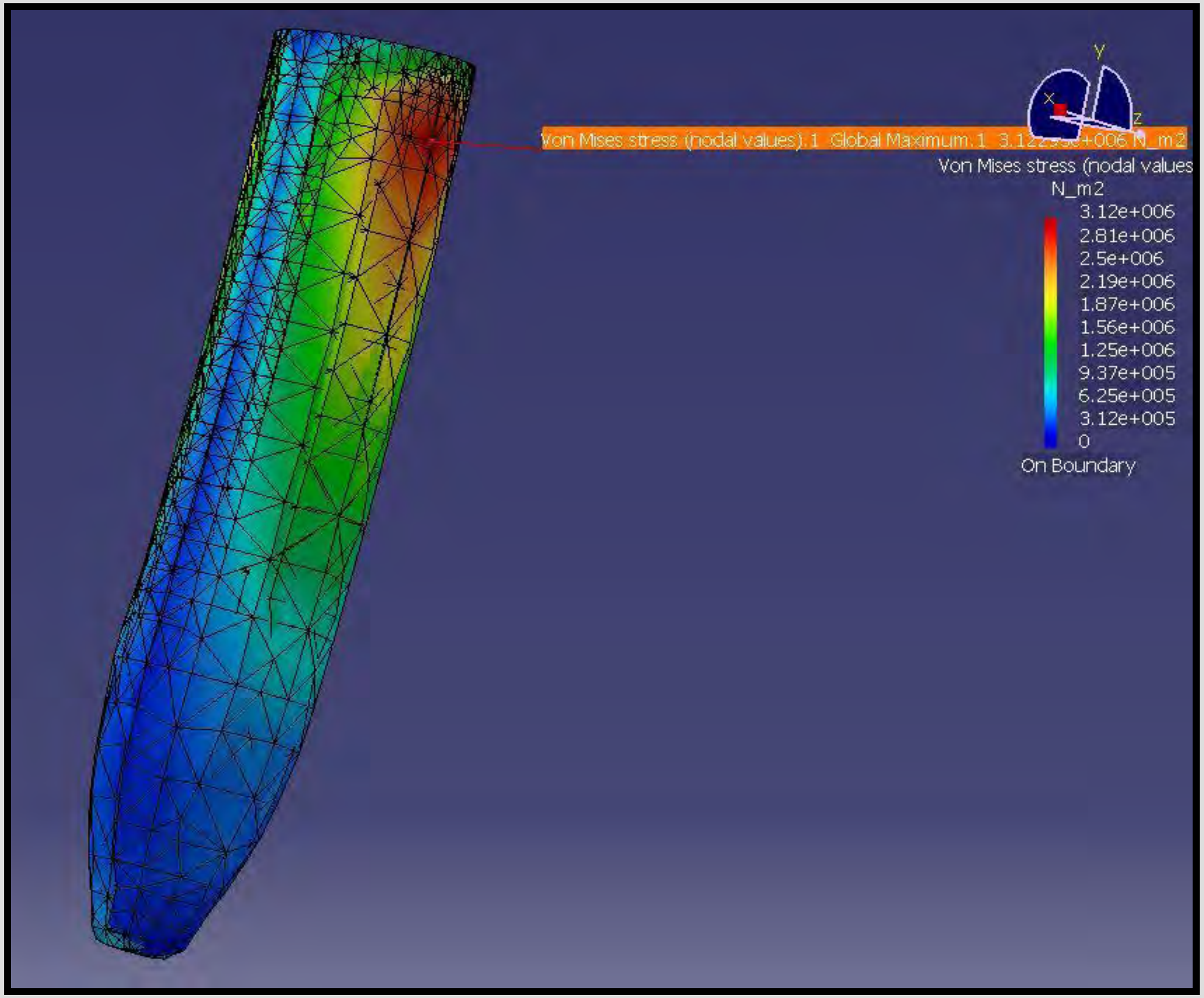
Case 2 – Lateral Loading

- The penetrator was evaluated for lateral loading to account for effects of variation in angle of attack
- A model of the penetrator is created using modeling software
- The model is constrained and lateral loads applied to identify stress, displacement, and deformation characteristics

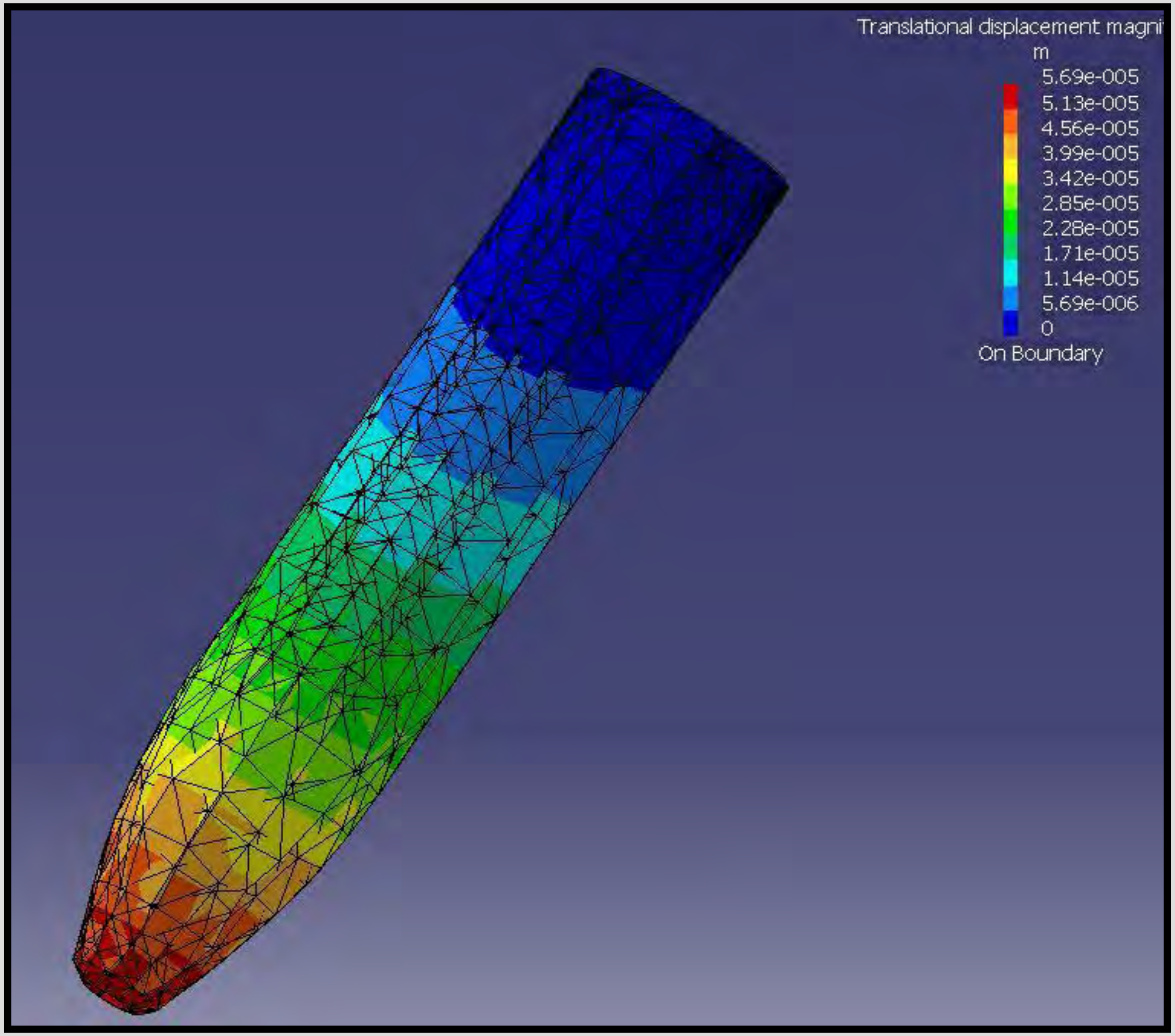
Lateral Loading



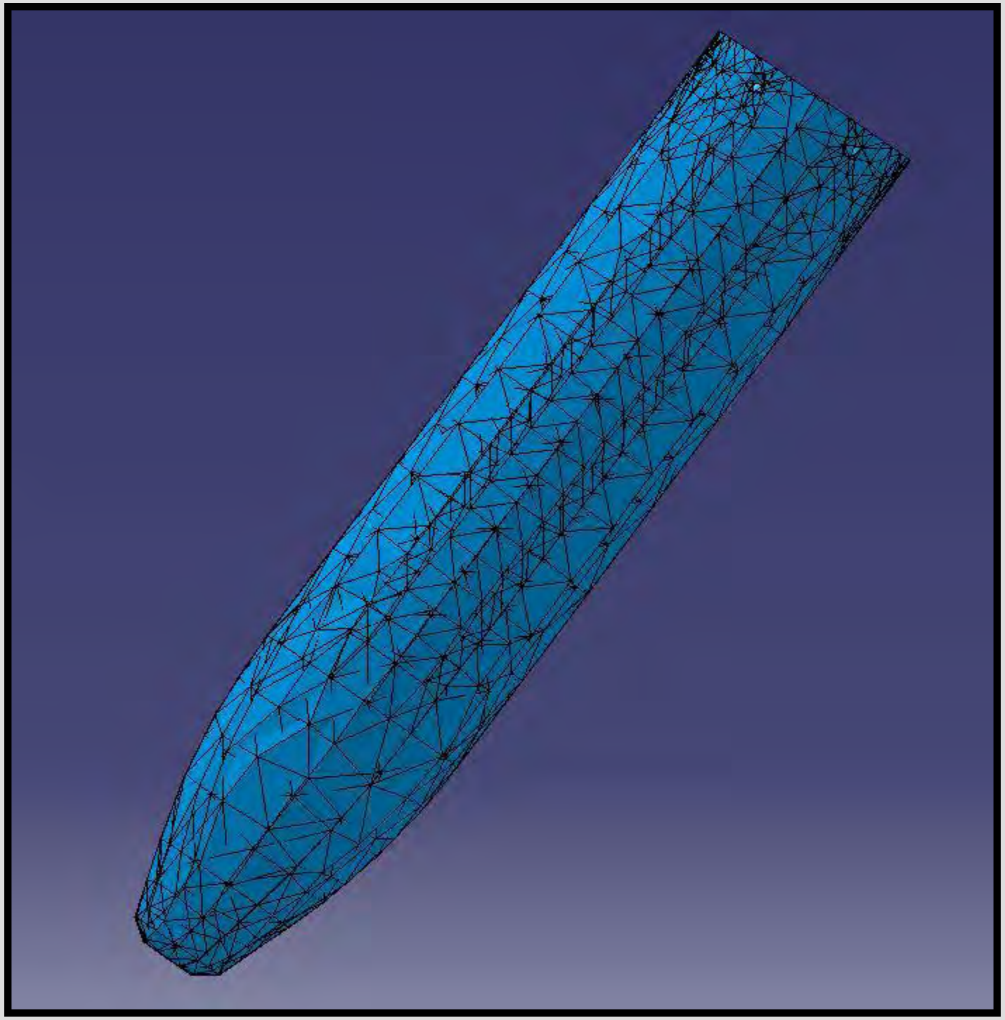
Von Mises Stress (Nodal Values)



Translational Displacement Magnitude



Deformation Characteristics



Quantitative Results

Lateral Loading Analysis

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Elements	24792

ELEMENT TYPE:

Connectivity	Statistics
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Materials.1

Material	Tungsten
Young's modulus	4e+011N_m2
Poisson's ratio	0.31
Density	16870kg_m3
Coefficient of thermal expansion	5.58e-006_Kdeg

Results

- The penetrator was evaluated for vertical and lateral loading
- Lateral Loading was considered to evaluate effects of variation in angle of attack
- Penetrator performed well in case of vertical loading
- In lateral loading it suffered increased deformation and stresses

Recommendations

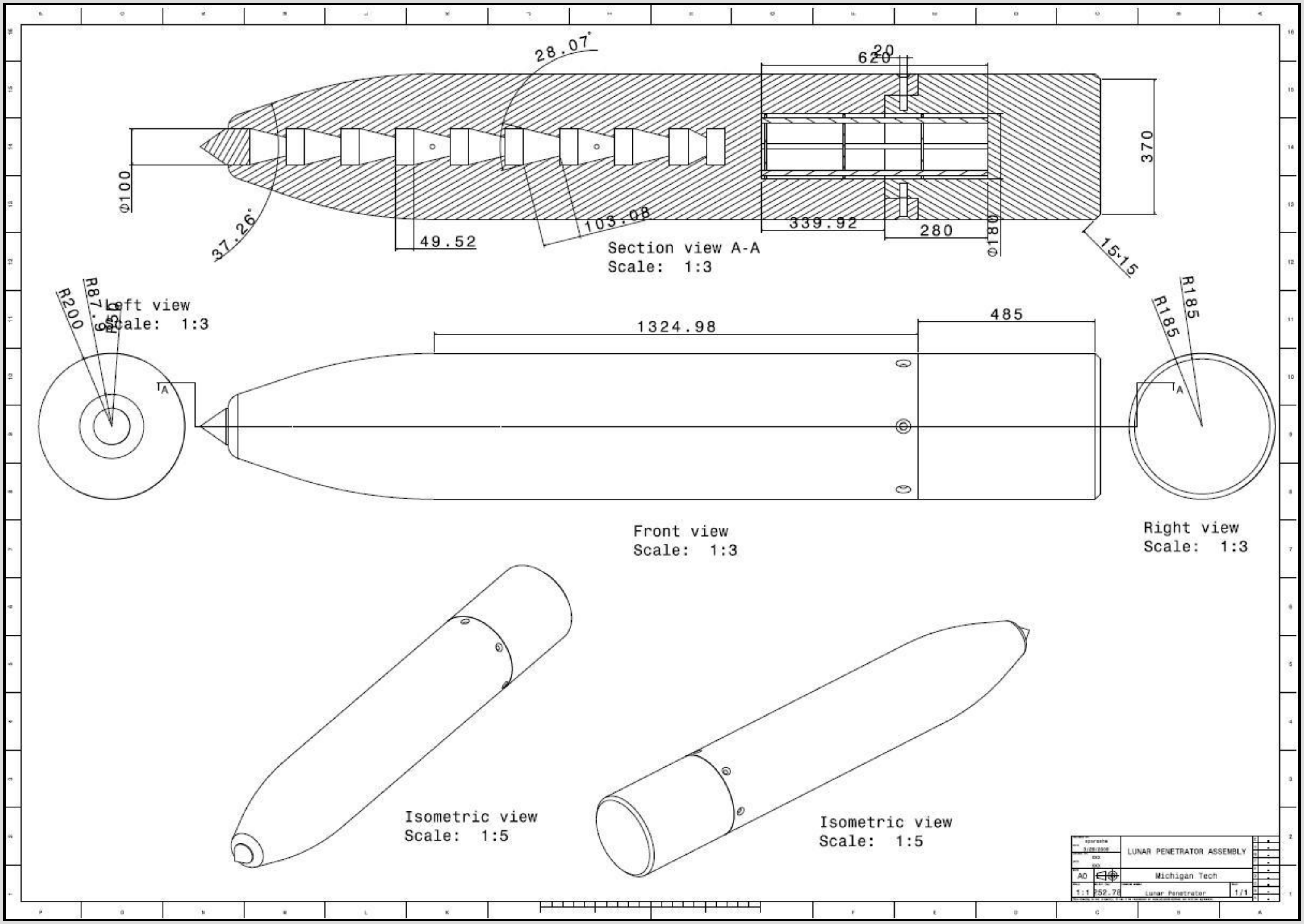
- Effective navigation and attitude control would be needed to maintain the angle of attack
- Crash analysis with surface simulation capabilities is recommended to further corroborate the results
- Results are presented to sponsor in proper format with detailed simulation results

Detailed Part and Assembly Drawings

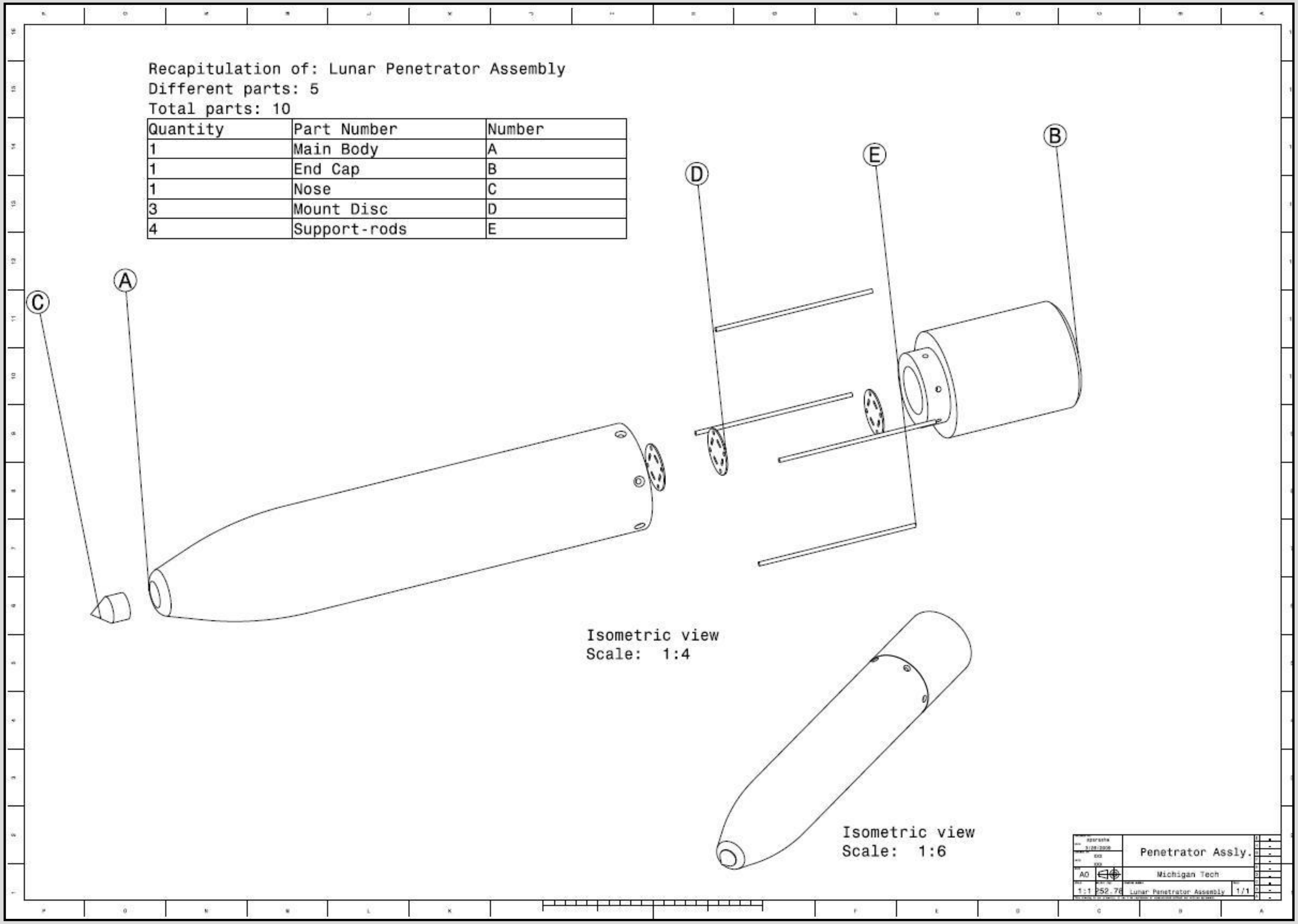
Detailed Drawings

- Detailed part and assembly drawings were created using modeling and drafting software
- Care was taken to include title blocks, bill of materials, *etc*.
- Adequate views were included for clear understanding

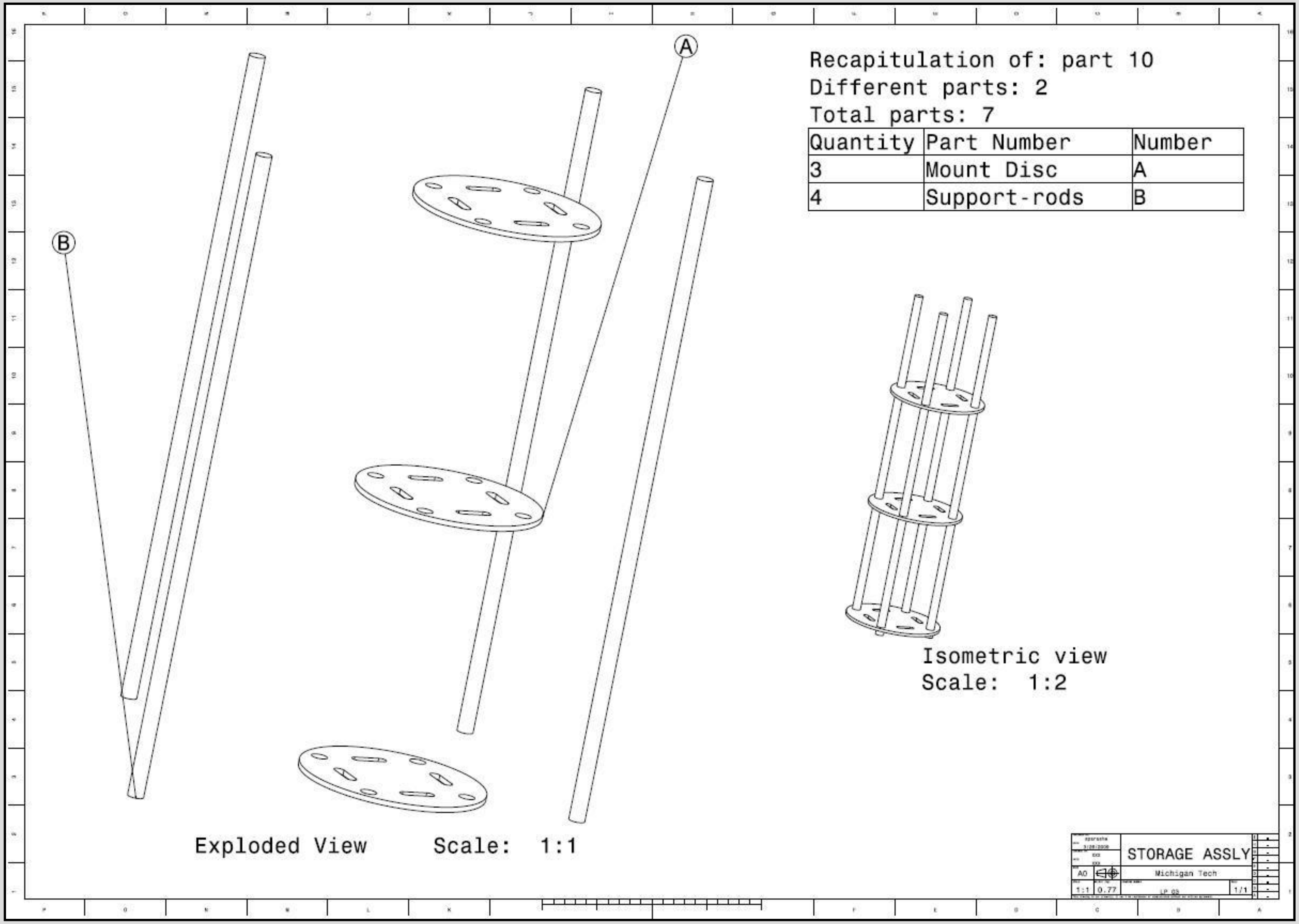
Product Drawing – Lunar Penetrator



Assembly Drawing – Penetrator

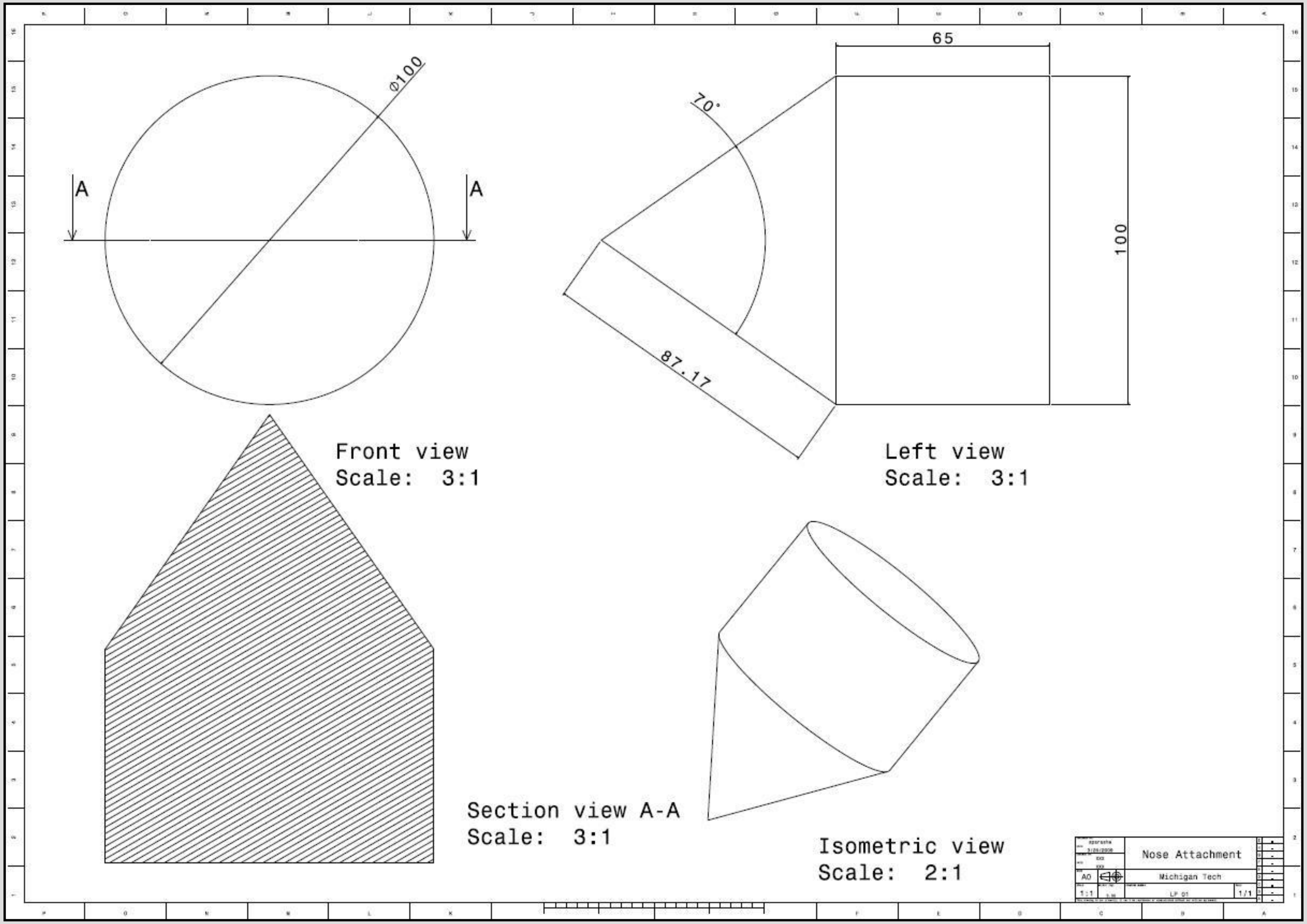


Assembly Drawing – Storage Assembly

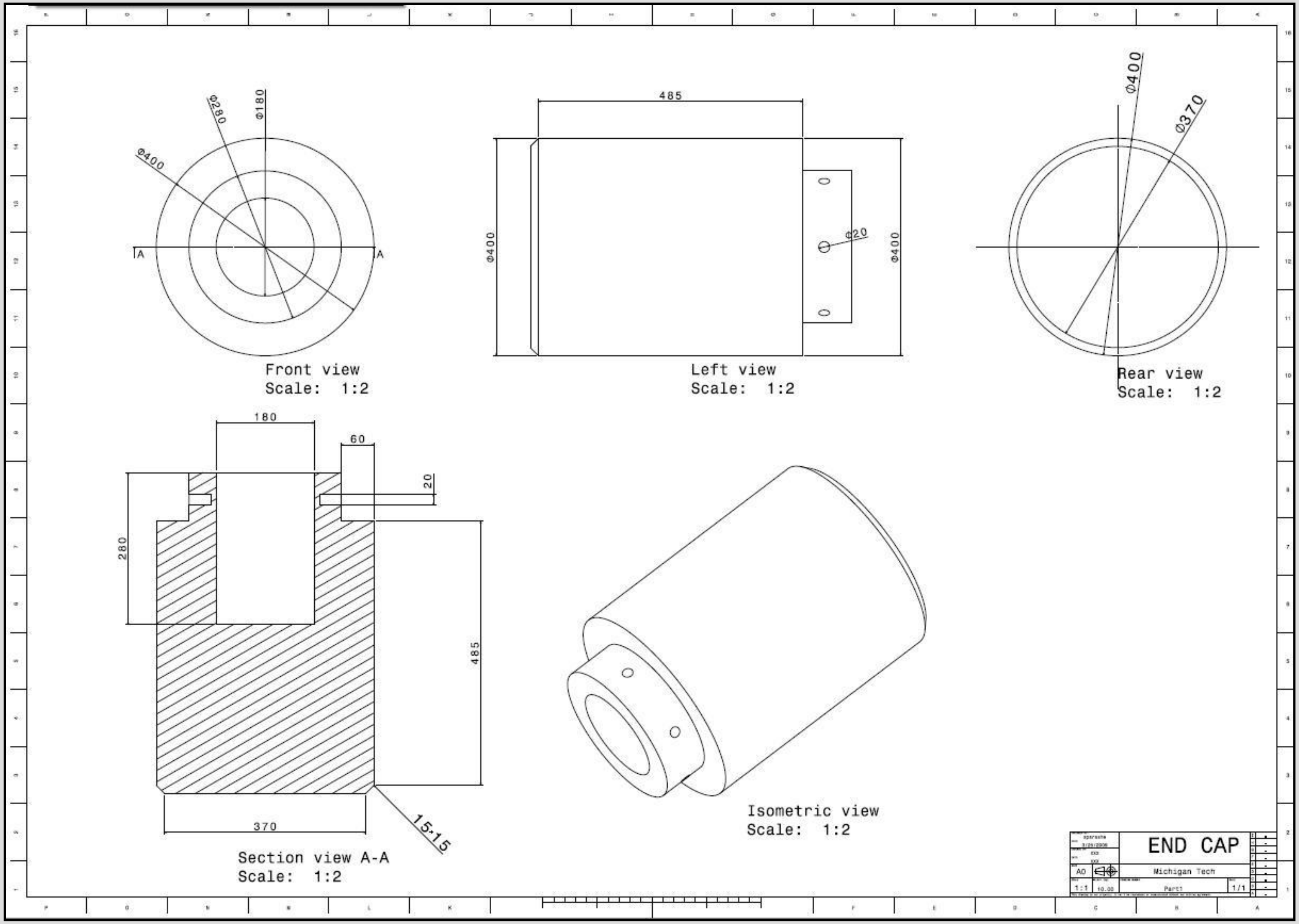


Quantity	Part Number	Number
3	Mount Disc	A
4	Support-rods	B

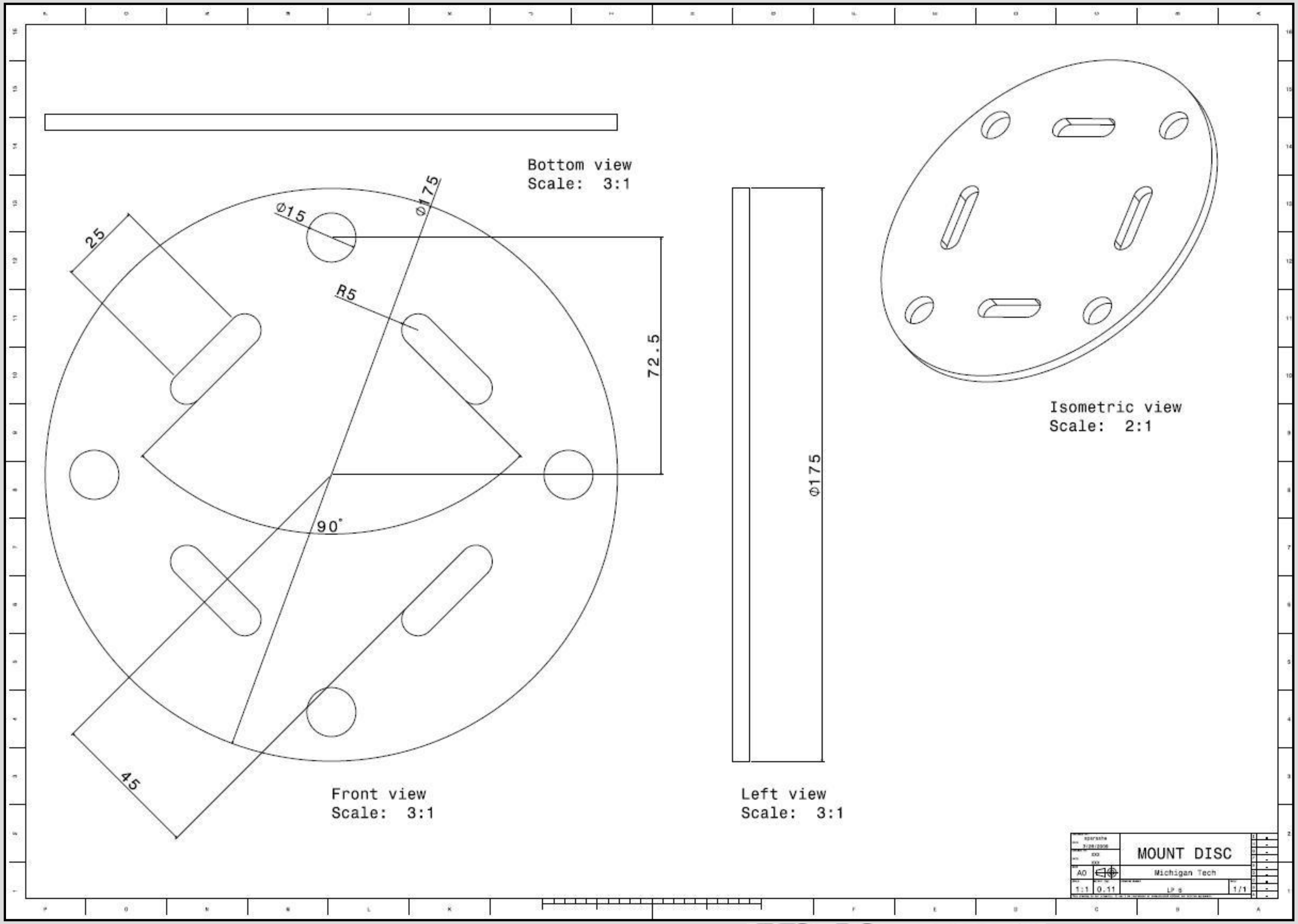
Part Drawings – Nose Attachment



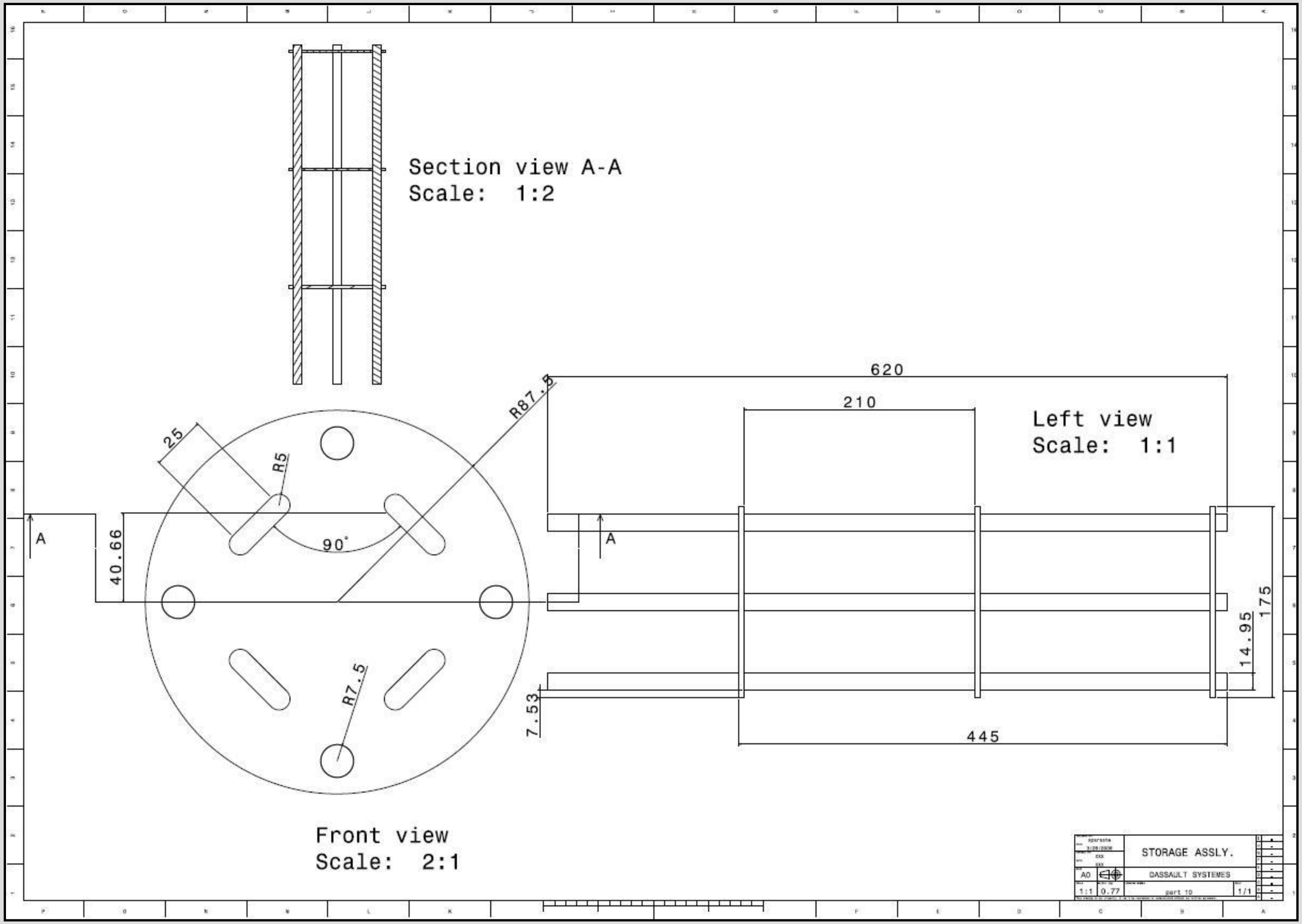
Part Drawings – End Cap



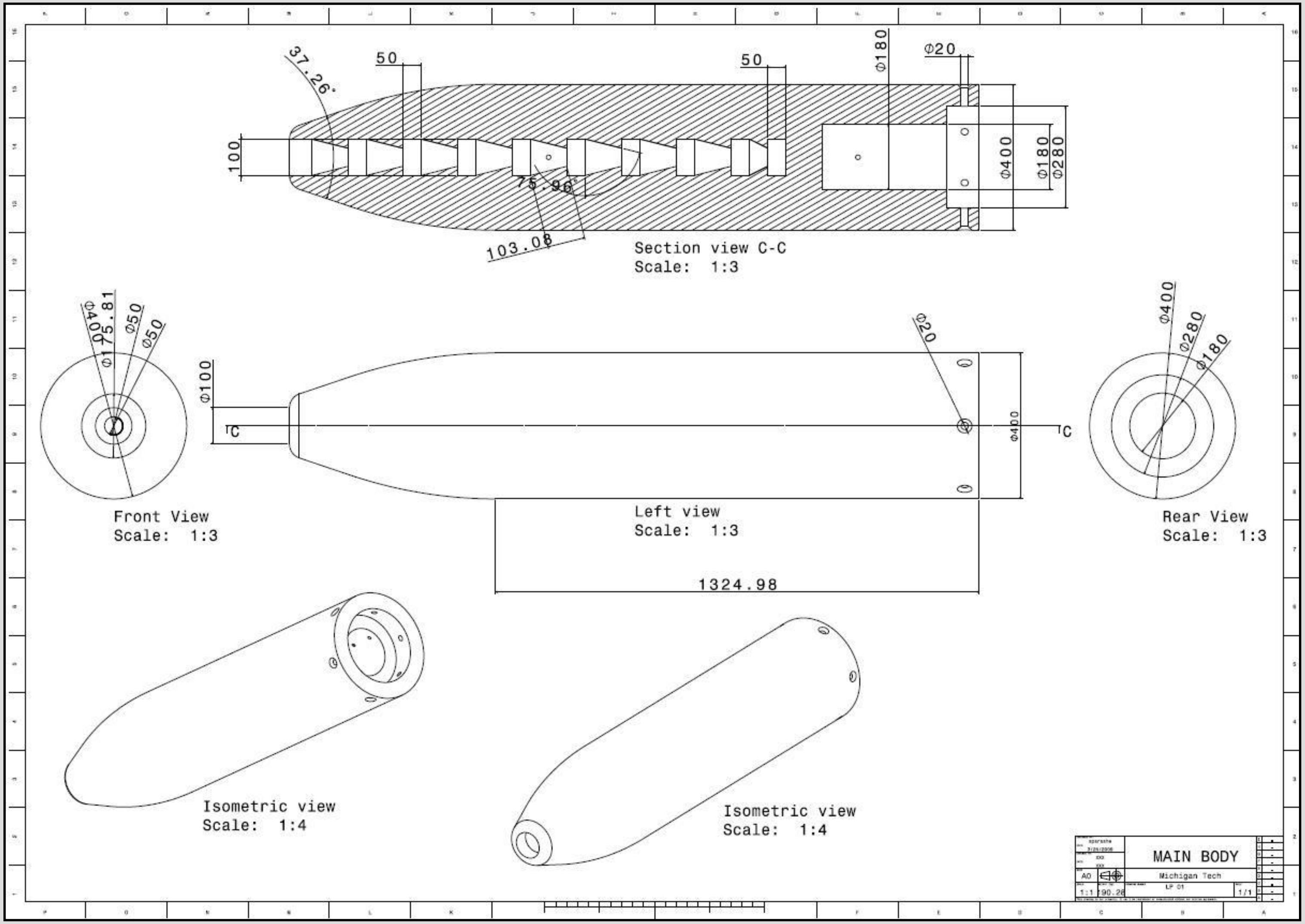
Part Drawings – Mount Disc



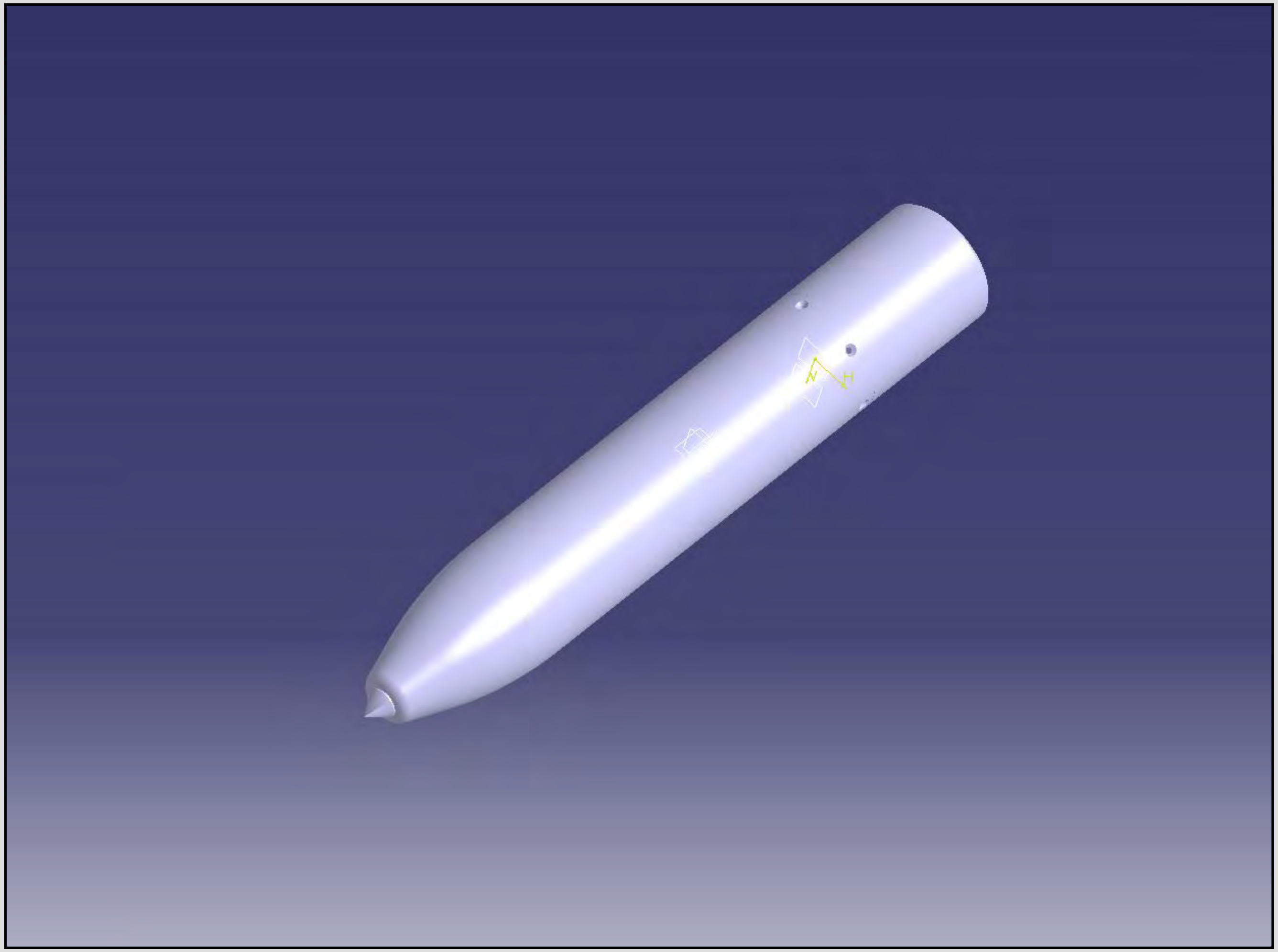
Part Drawings – Storage



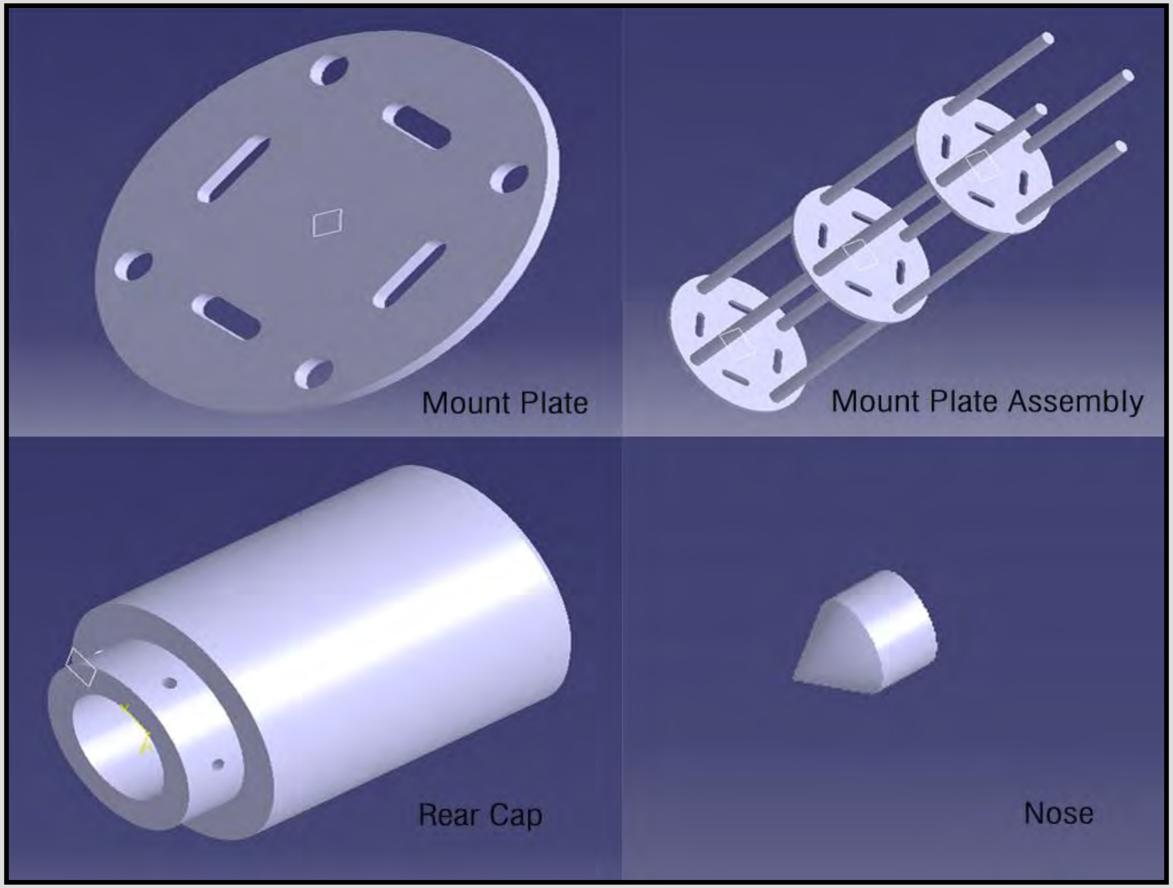
Part Drawings – Main Body



3-D Model – Penetrator



3-D Part Models



Parameter Level Design Proposal

Design Evaluation Summary Report

Design Evaluation Summary Report

Design of a Lunar Penetrator

Evaluation of the success of each design objective ranked in order of user ratings:

1. **Adequate power supply – Target: 300 Ah capacities:** The system for the batteries suggested offers a capacity of 280 Ah to power all equipment s needed to acquire and transmit data over a span of 1 week.
   Conclusion: Achieved capacity of 280 Ah is below the desired target value, but it is possible to reach the target by providing better temperature insulation to the battery packs. If smaller battery packs are found at a relatively low price, additional capacity can be added to reach the desired target of 300 Ah.

2. **High strength and impact survival – Target: Survive 3000G impact**: The simulation models of the penetrator proved their survivability for loading as high as 50000 N. However, when laterally loaded, it shows survivability for 30000 N loading only. The stress, deformation, and displacement characteristics were within limits so as to prevent any harm to the overall integrity of the penetrator structure or to the contents within.
   Conclusion: The target was achieved. Further simulations using powerful dynamic simulation software using crash testing on to simulated lunar surface is suggested in order to further corroborate the results.

3. **Space for accommodation of equipment – Target: Three compartments:** The payload accommodation structure consists of mount plates that are assembled together in a stacked fashion using rods. This setup provides three - level storage for the equipment and batteries and provides room for effective heat transfer also.
   Conclusion: The target is met successfully.

4. **Movable parts – Target: Zero movable parts:** The penetrator is an assembly of a nose, main body, payload equipment, and bottom cap. It forms an integral structure without any movables. The mount plates for payload are adjustable by manipulating lock nuts.
   Conclusion: Target achieved.

5. **Low Weight – Target: Less than 35 kgs:** Total weight of the penetrator, fully loaded, goes to approximately 40 kgs.
   Conclusion: The weight exceeds the target value of 35 kgs, however if need be, this value can be brought down by optimizing certain design characteristics.

6. **Low Cost – Target: Less than $4200:** The total cost of building the penetrator comes out to be approximately $ 4600. This includes all the material costs, machining costs and labor costs.
   Conclusion: This number of the cost is greater than the set target of keeping the expenses below $ 4200. However, if the battery packs are scaled down, this cost can be brought closer to the targeted value.

Design of a Lunar Penetrator
NASA ESMD Capstone Design

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NASA ESMD

Capstone Design Course

First Annual Space Grant Faculty Senior Design Training

developed by

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